The J-PARC muon g-2/EDM experiment

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On behalf of the J-PARC muon g-2/EDM collaboration

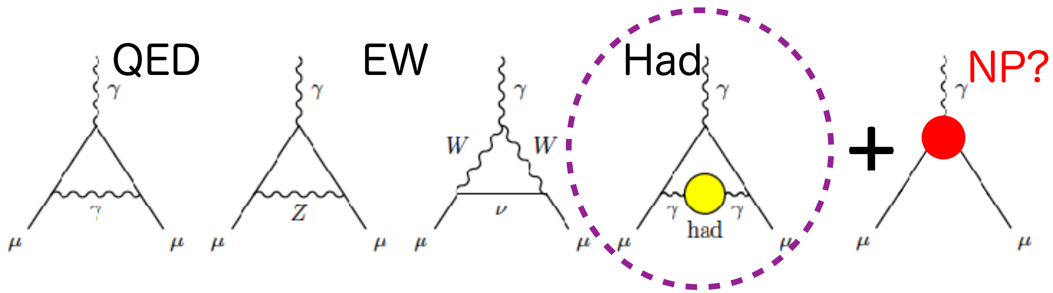
Muon g-2 and EDM (1)

- Muon anomalous magnetic moment (a_μ)
  - Deviation of g_μ from "2", the prediction of Dirac equation for fermions.
  - Precisely calculated in the SM and measured in the BNL+FNAL experiments.
    - ➢ δSM: 0.37 ppm ("White paper")
    - ➢ δexp: 0.35 ppm (BNL+FNAL)
  - 4.2σ discrepancy between the SM and measurements.

Magnetic Dipole Moment

$$a_\mu = \frac{g-2}{2} \qquad \vec{\mu} = g\left(\frac{e}{2m}\right)\vec{s},$$

g: gyromagnetic ratio



"White paper": Phys. Rep. 887 (2020), 1-166.

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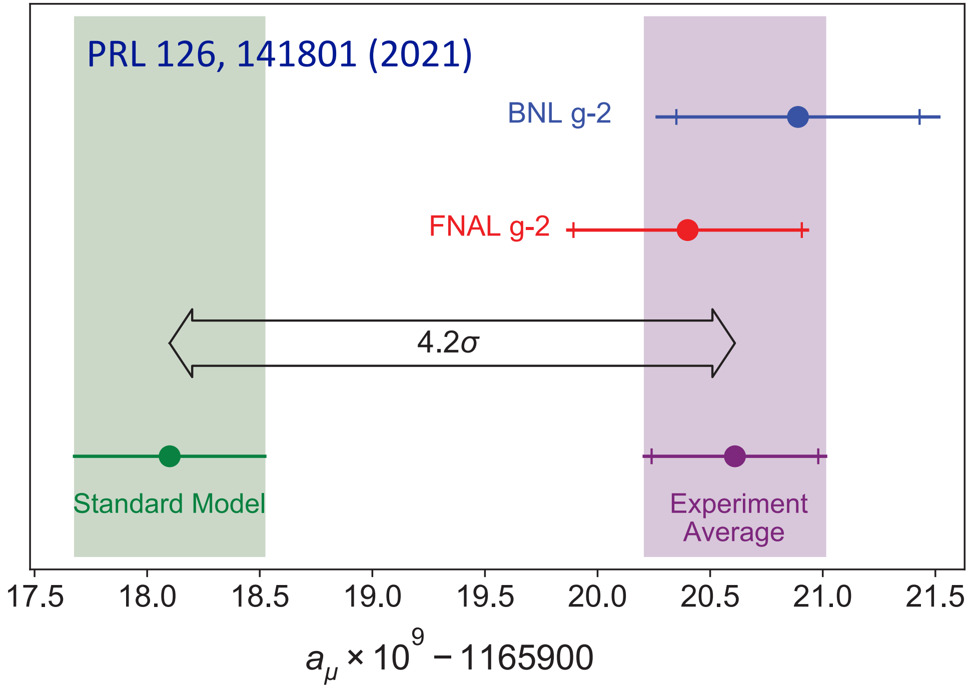
journal homepage: www.elsevier.com/locate/physrep

ELSEVIER

The anomalous magnetic moment of the muon in the Standard Model

T. Aoyama [1,2,3], N. Asmussen [4], M. Benayoun [5], J. Bijnens [6], T. Blum [7,8], M. Bruno [9], I. Caprini [10], C.M. Carloni Calame [11], M. Cè [9,12,13], G. Colangelo [14,*], F. Curciarello [15,16], H. Czyż [17], I. Danilkin [12], M. Davier [18,*], C.T.H. Davies [19], M. Della Morte [20], S.I. Eidelman [21,22,*], A.X. El-Khadra [23,24,*], A. Gérardin [25], D. Giusti [26,27], M. Golterman [28], Steven Gottlieb [29], V. Gülpers [30], F. Hagelstein [14], M. Hayakawa [31,2], G. Herdoíza [32], D.W. Hertzog [33], A. Hoecker [34],



Muon g-2 and EDM (1)’

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- One of the best probes for New Physics (NP) beyond the SM.
  - Need a new experimental approach as well as an improved precision.

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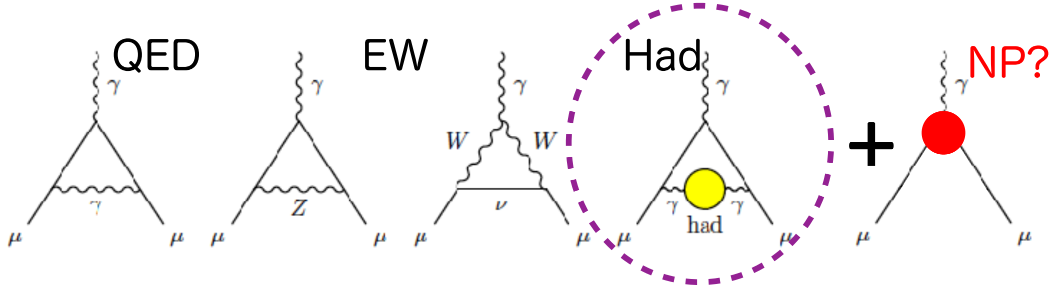

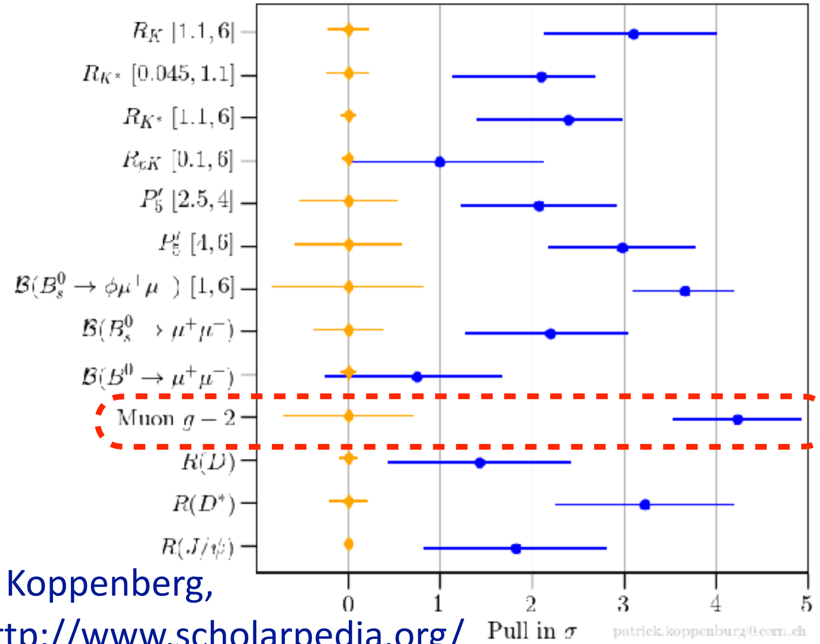

P. Koppenberg, http://www.scholarpedia.org/article/File:AnomaliesPlot.png

Muon g-2 and EDM (2)

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g: gyromagnetic ratio

Electric Dipole Moment

$$\vec{d} = \eta\left(\frac{e}{2mc}\right)\vec{s}.$$

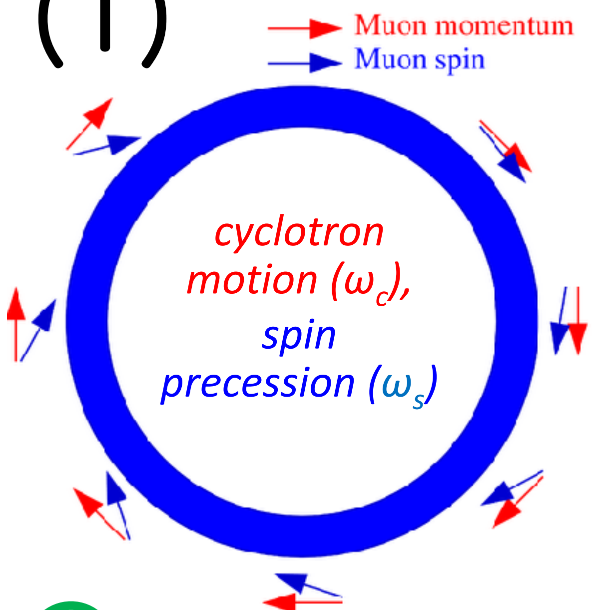
- Electric Dipole Moment (EDM, d_μ)
  - Can be measured in parallel with a_μ.
  - $d_\mu \neq 0$ indicates T-violation, hence CP-violation, in the lepton sector.
    - ➢ SM: 2×10^{-38} e・cm,
    - ➢ Exp: < 1.8×10^{-19} e・cm (90% C.L. in BNL E821)
  - Another probe for NP.

Experimental approach (1)

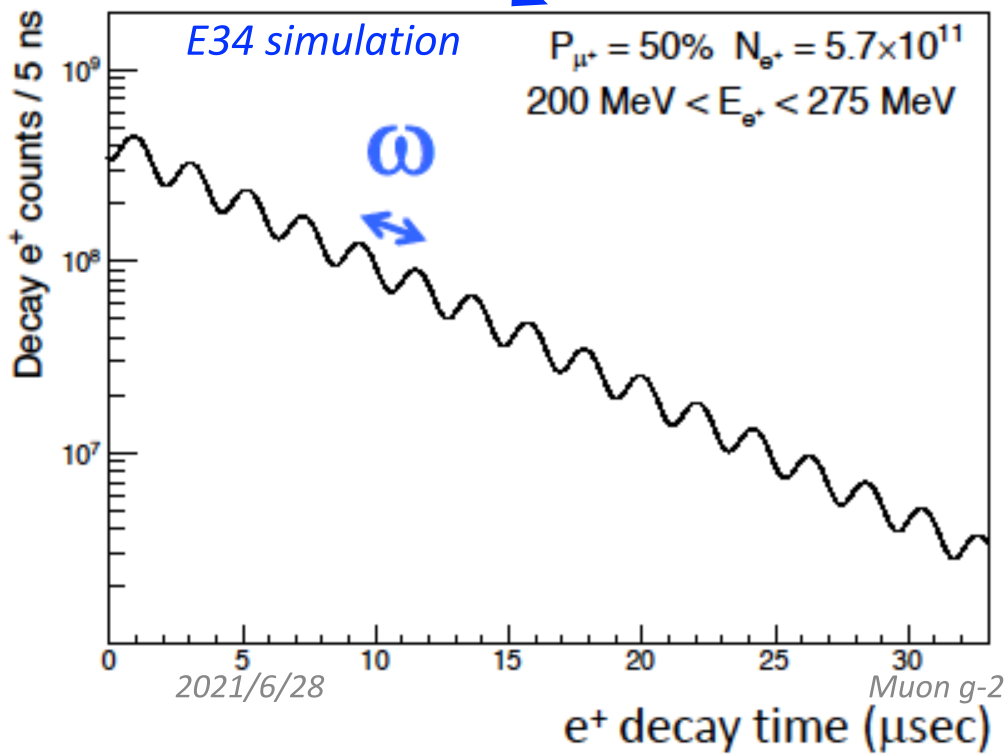
- Measure the "beat" frequency (ω) to extract a_μ and η.

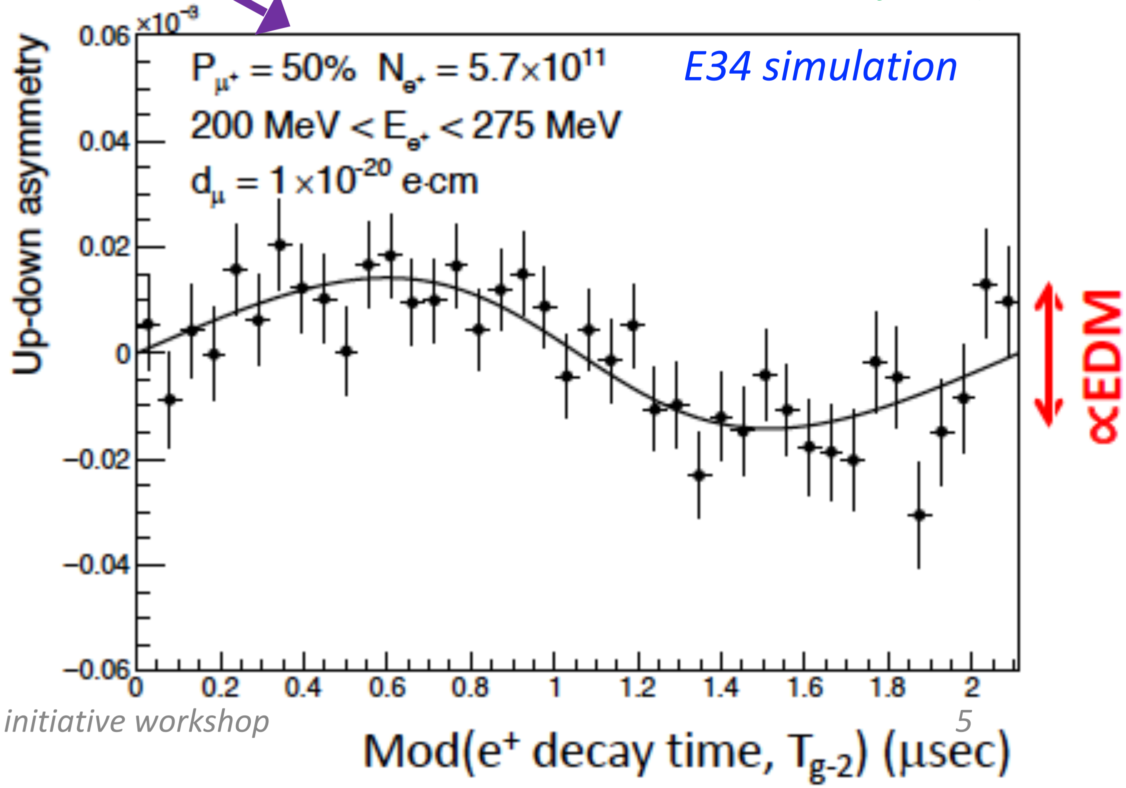
$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_\eta$$

$$= -\frac{e}{m}\left[\underbrace{a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}}_{\omega_a\ (=\ \omega_s - \omega_c)} + \underbrace{\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)}_{\omega_\eta}\right]$$



In a uniform B field (top view in lab. frame)





Experimental approach (2)

- Eliminate the βxE term for simplification.
  - "Magic momentum" (p_μ = 3.1 GeV/c).

p= 3.09 GeV/c , B=1.45 T

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_\eta$$

$$= -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

$\left(a_\mu - \frac{1}{\gamma^2 - 1}\right) = 0$

BNL E821 approach

γ=29.3 (p=3.09 GeV/c)

$$= -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

FNAL E989

- Items related to the major systematic uncertainties (BNL)
  - Strong focusing E field,
    - ➢for the large phase-space beam,
  - B field non-uniformity,
  - Detector pile-up.
    - ➢in calorimeter.

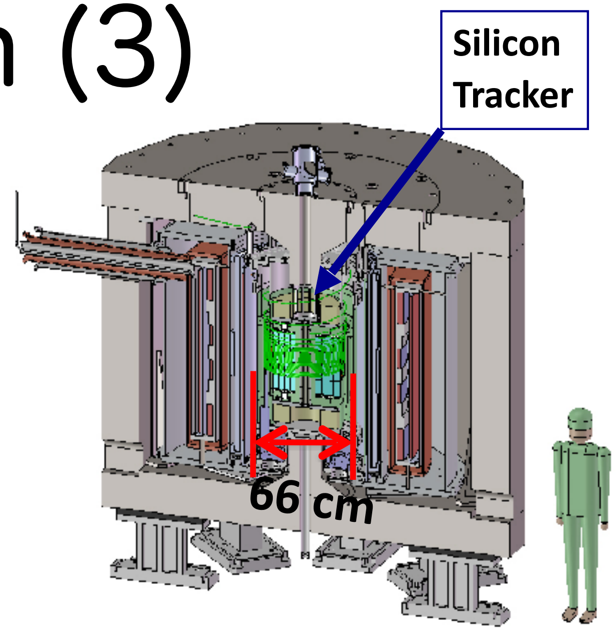
Experimental approach (3)

- Eliminate the βxE term for simplification.
  - "Magic momentum" (p_μ = 3.1 GeV/c).
  - Nearly no E field with "ultra-cold muon beam"

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_\eta$$

$$= -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

($\vec{E}$ = 0, $\vec{E}$ = 0)



Super Precision Storage Magnet
(3T, ~1ppm local precision)

- Extraction of a_μ

$$a_\mu = \frac{R}{\lambda - R}$$

$R = \omega_a / \omega_p$ (ω_p: Larmor freq. of a free proton) → NMR probe

$\lambda = \mu_\mu / \mu_p$ (μ_p: proton magnetic moment) → Mu hyperfine splitting (MuSEUM)

J-PARC approach
E = 0 at any γ

$$= -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

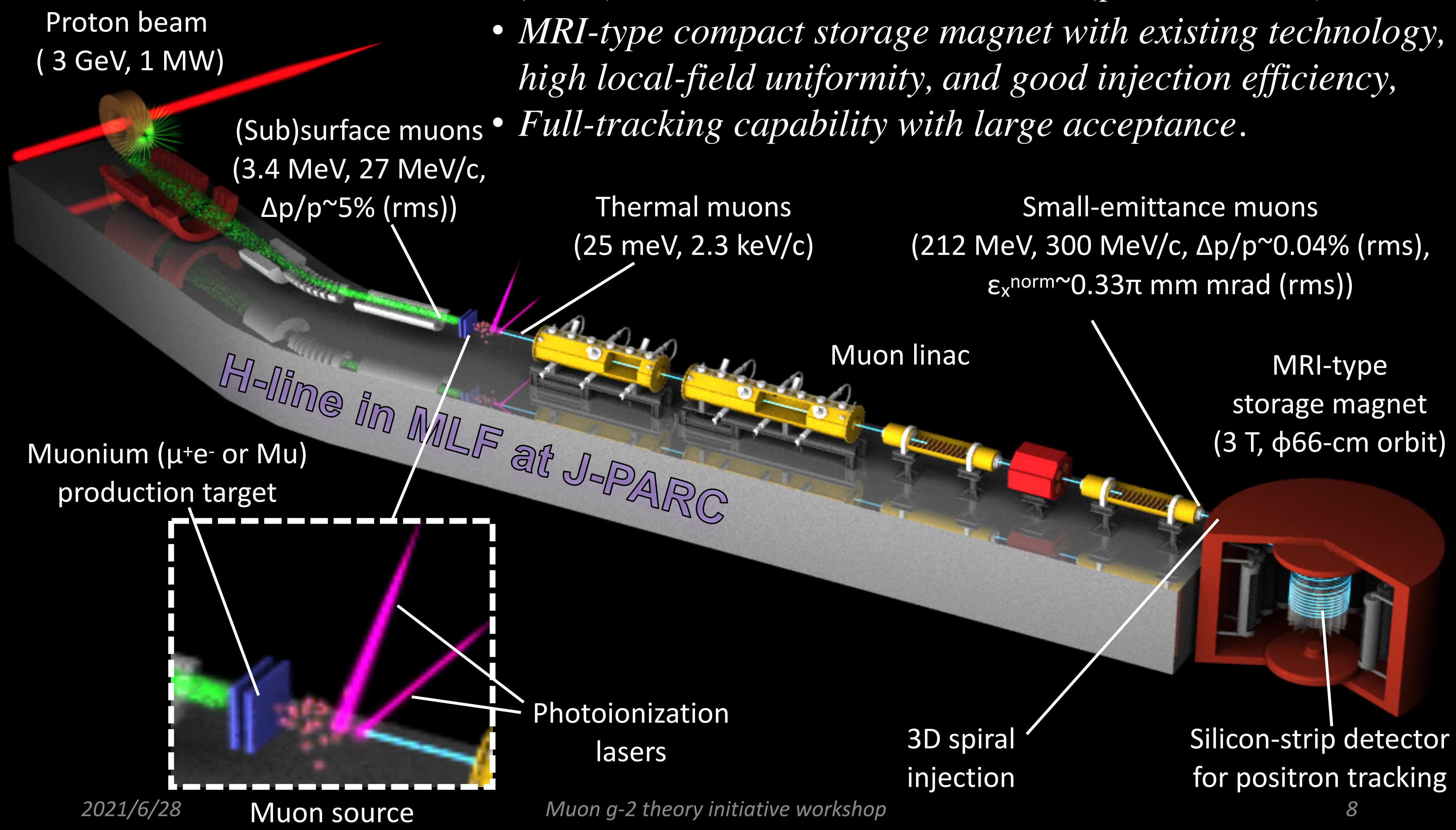
J-PARC E34

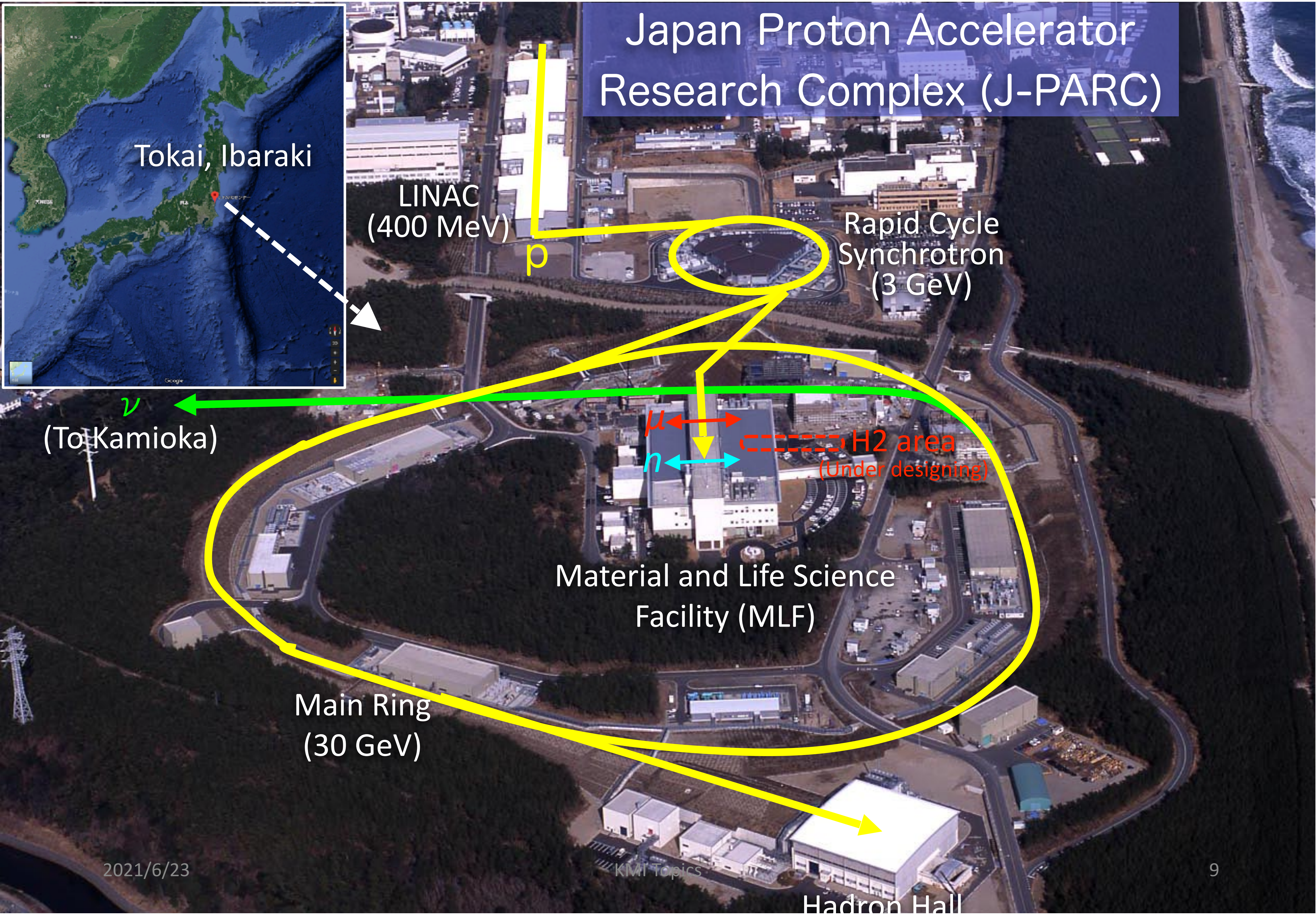
- Small-emittance beam,
- Weak focusing B field,
- Compact NMR-type storage magnet with excellent uniformity (Δ~0.1 ppm),
- Silicon strip detector with tracking capability.

A new measurement with completely different systematics is possible.

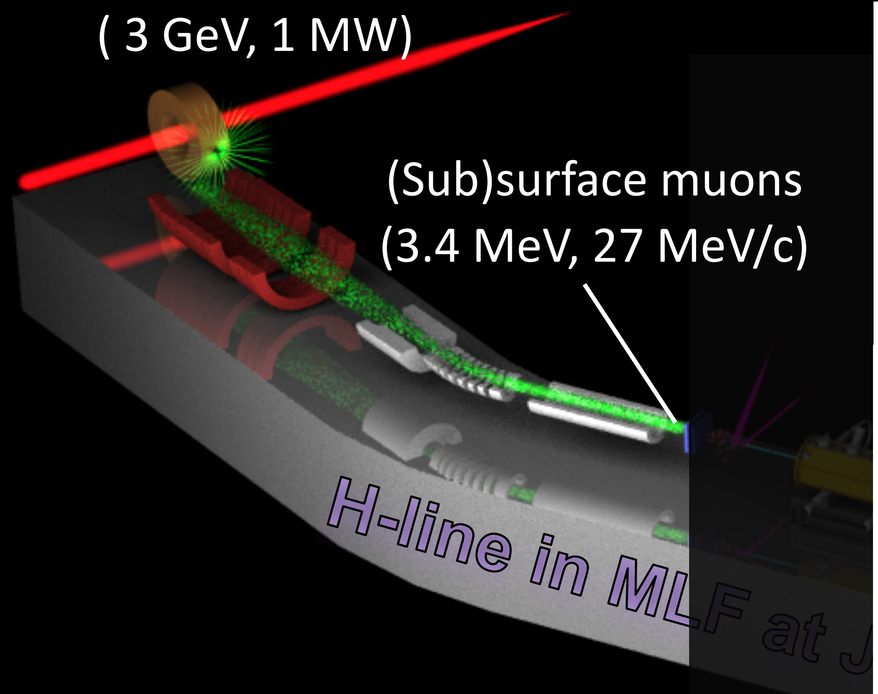
J-PARC muon g-2/EDM experiment

- *Small-emittance muon beam, therefore, no strong focusing ($E \simeq 0$) and no momentum constraint (p=300 MeV/c).*
- *MRI-type compact storage magnet with existing technology, high local-field uniformity, and good injection efficiency,*
- *Full-tracking capability with large acceptance.*

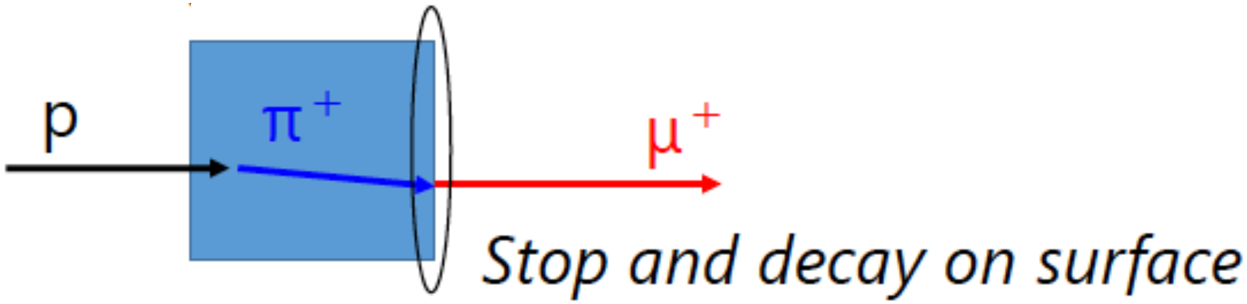



Japan Proton Accelerator Research Complex (J-PARC)
Tokai, Ibaraki
LINAC (400 MeV)
p
Rapid Cycle Synchrotron (3 GeV)
ν
(To Kamioka)
μ
n
H2 area
(Under designing)
Material and Life Science Facility (MLF)
Main Ring (30 GeV)
Hadron Hall

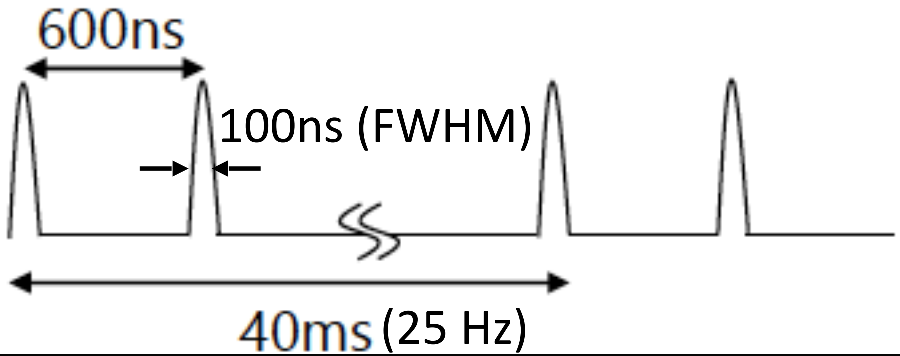
Surface muon beamline (1)



- (Sub)surface muons
  - μ^+ decayed from π^+ stopped at or near the target surface.
  - 100%-polarized and monochromatic (not for the subsurface muons).

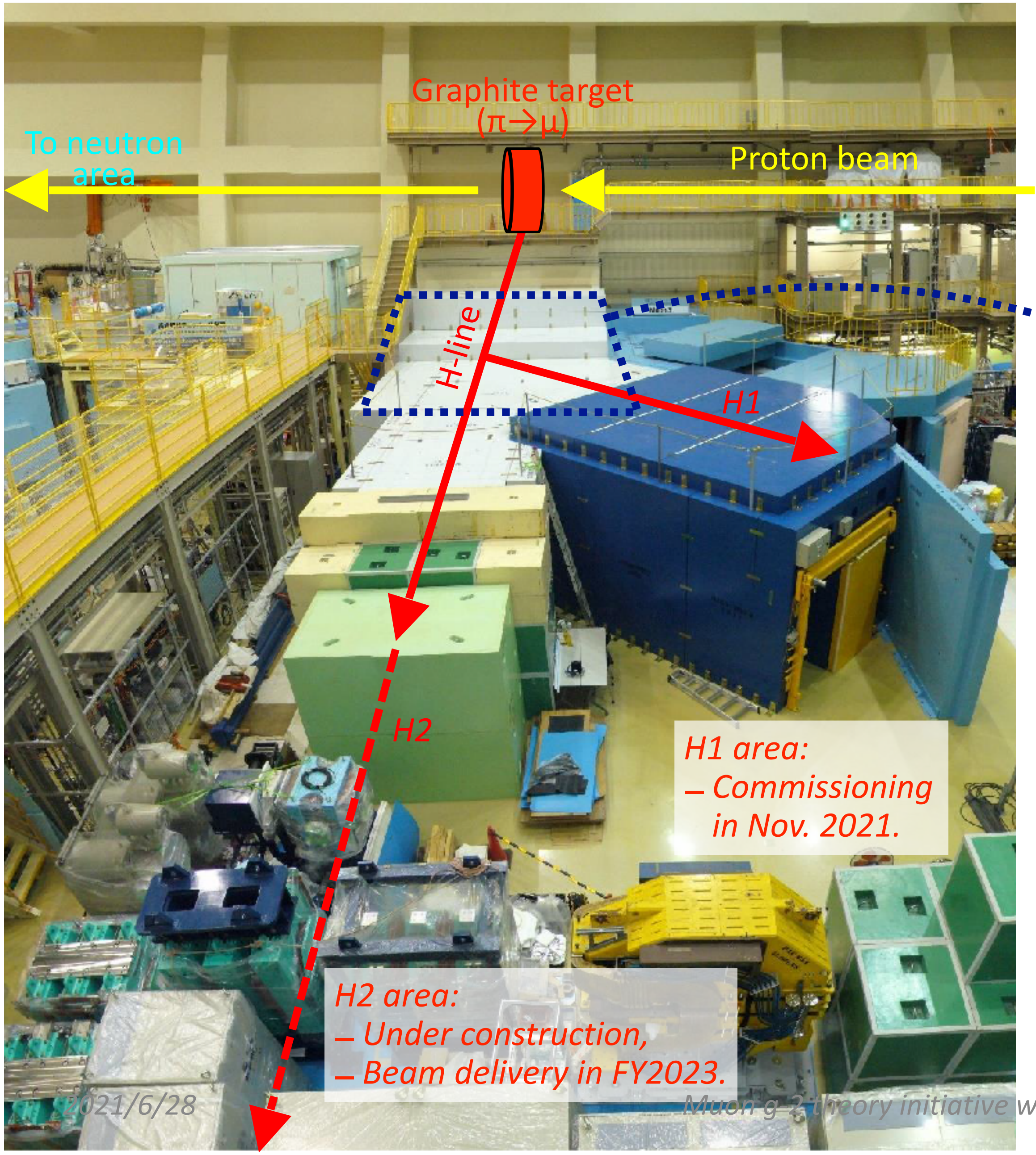


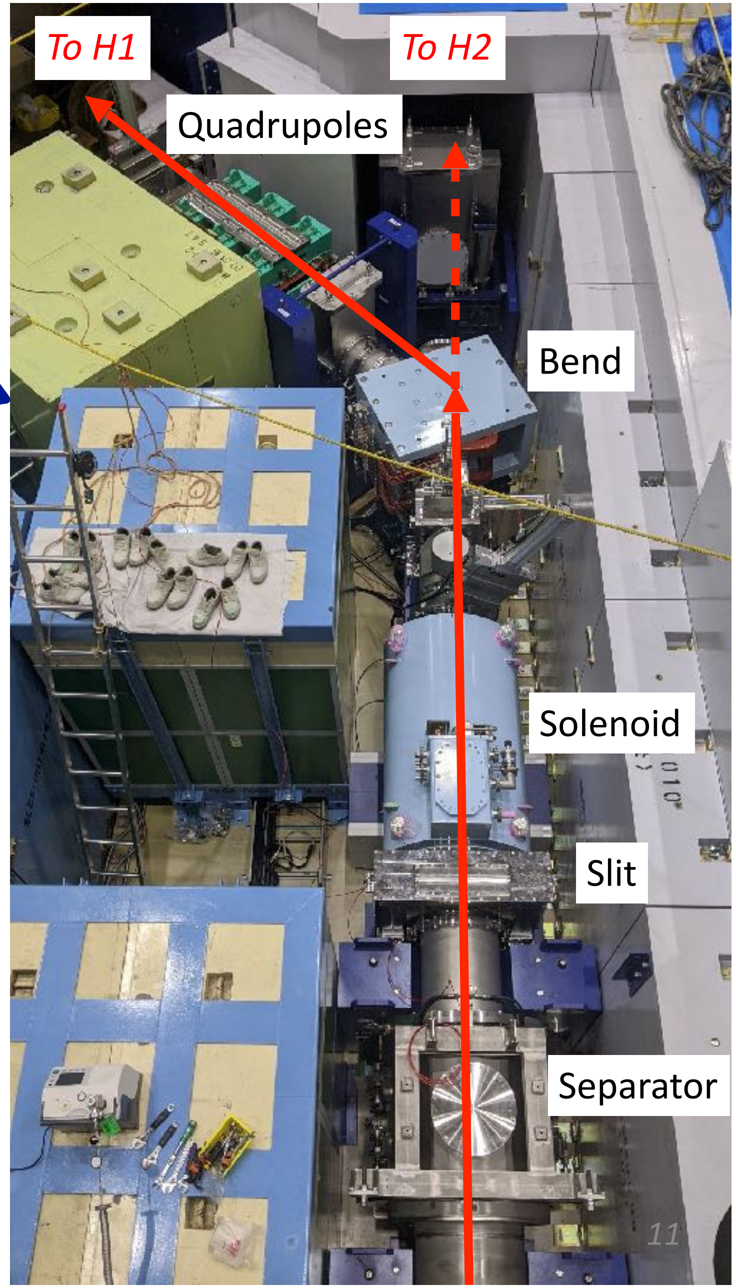
- H-line at J-PARC MLF
  - Double pulse structure at 25 Hz repetition,
  - Intensity: ~10^8 μ^+/s.



Surface muon beamline (2)

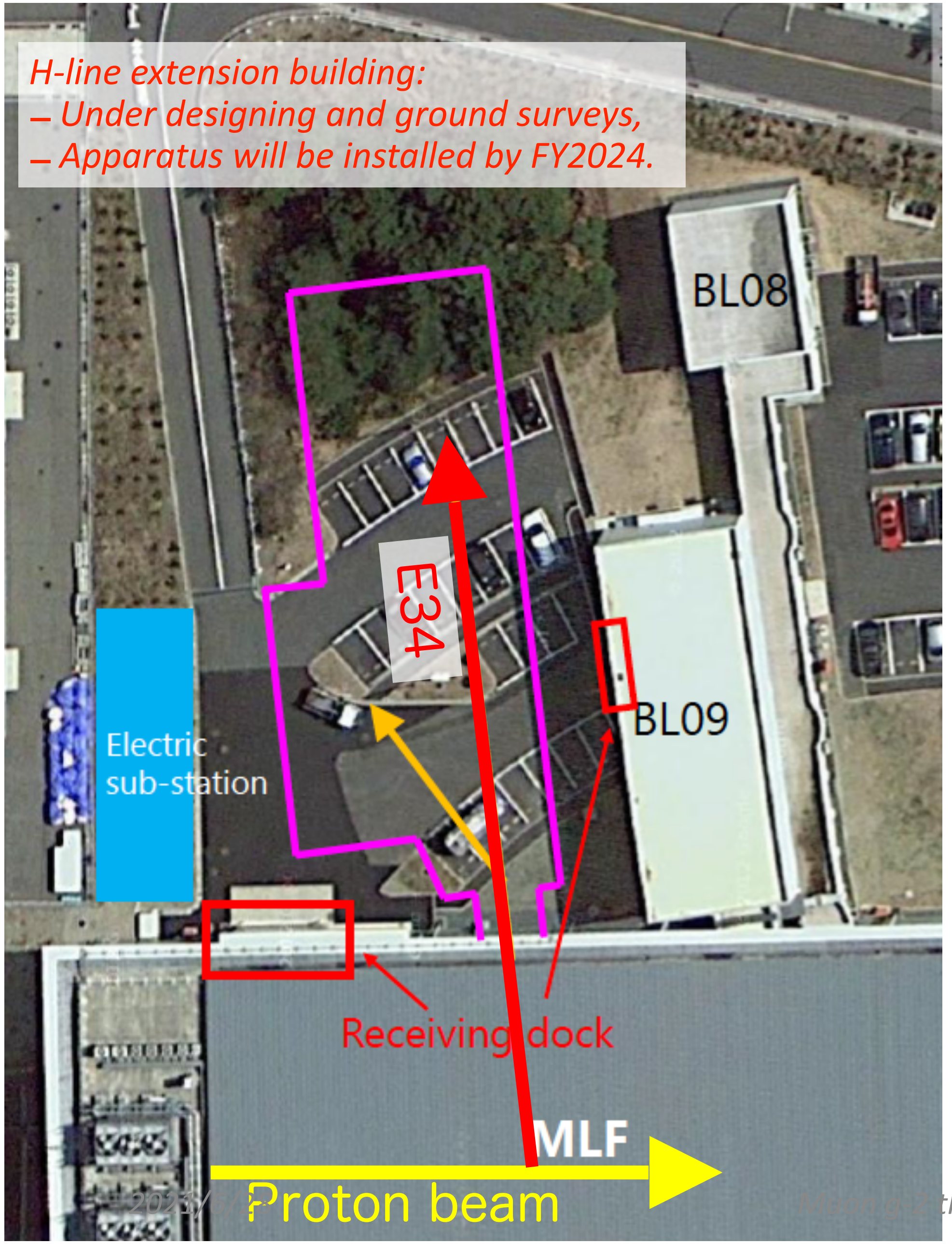
- The beamline commissioning will start in November 2021.

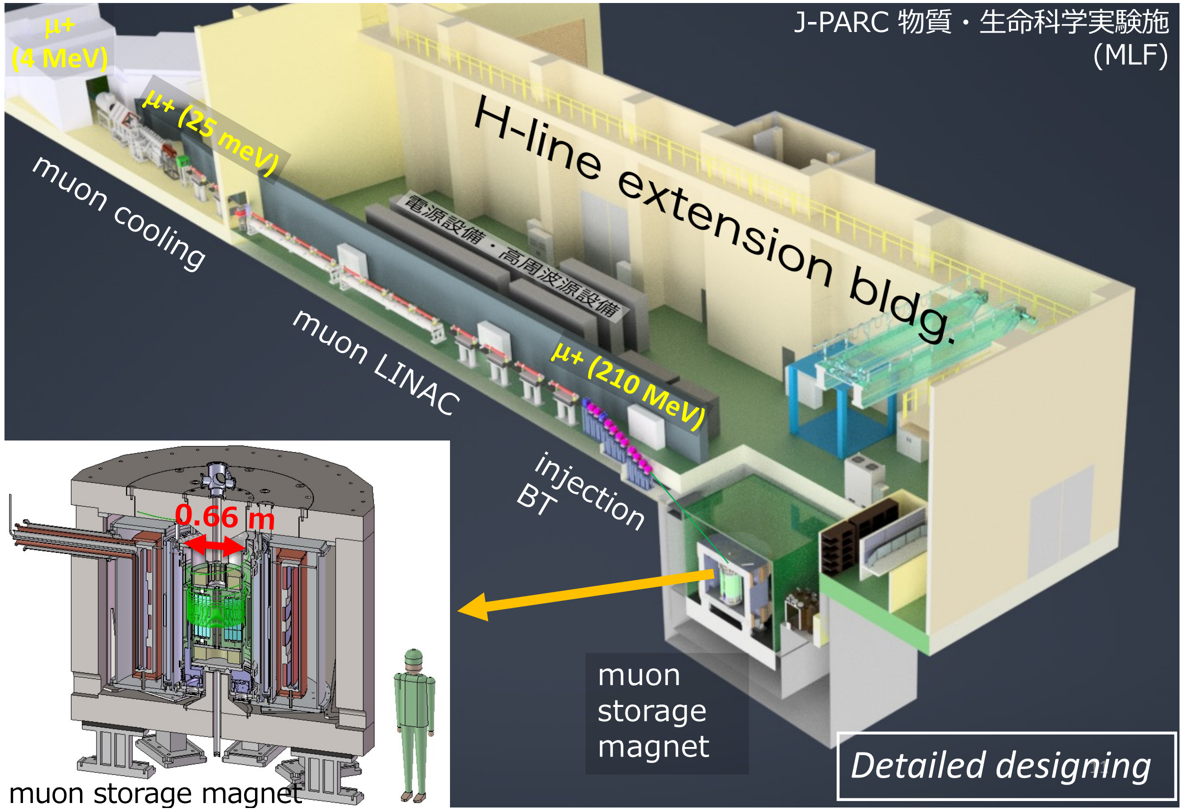




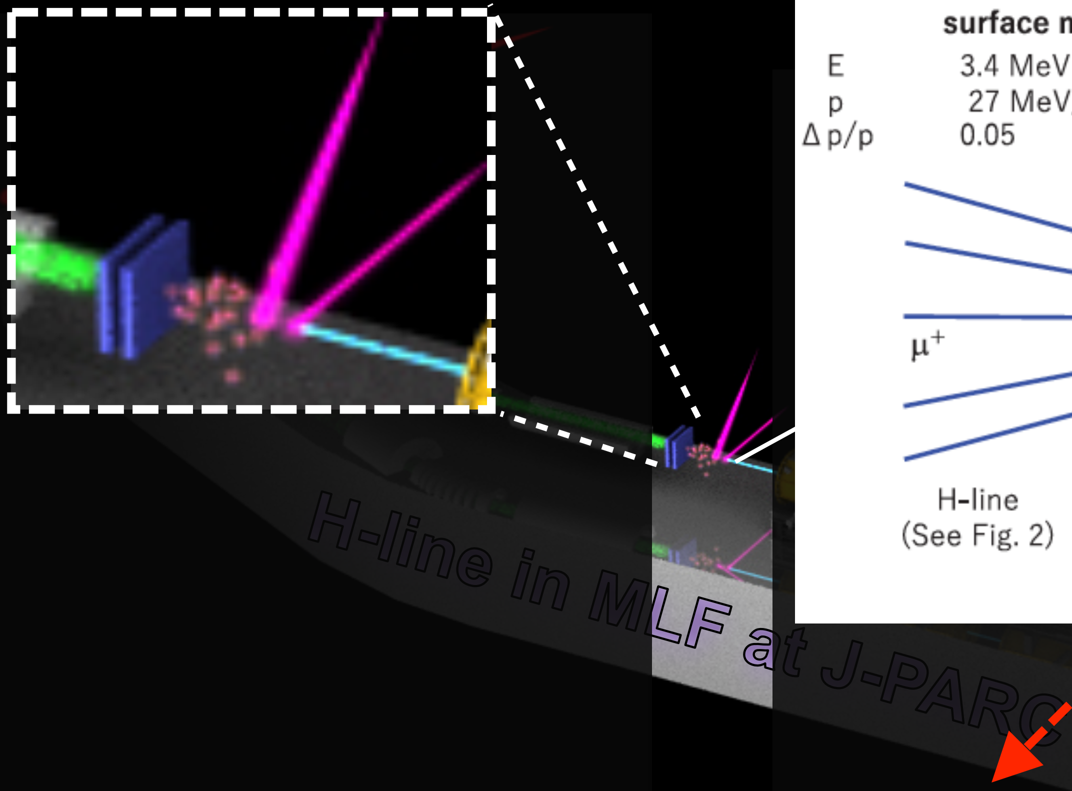
Surface muon beamline (3)

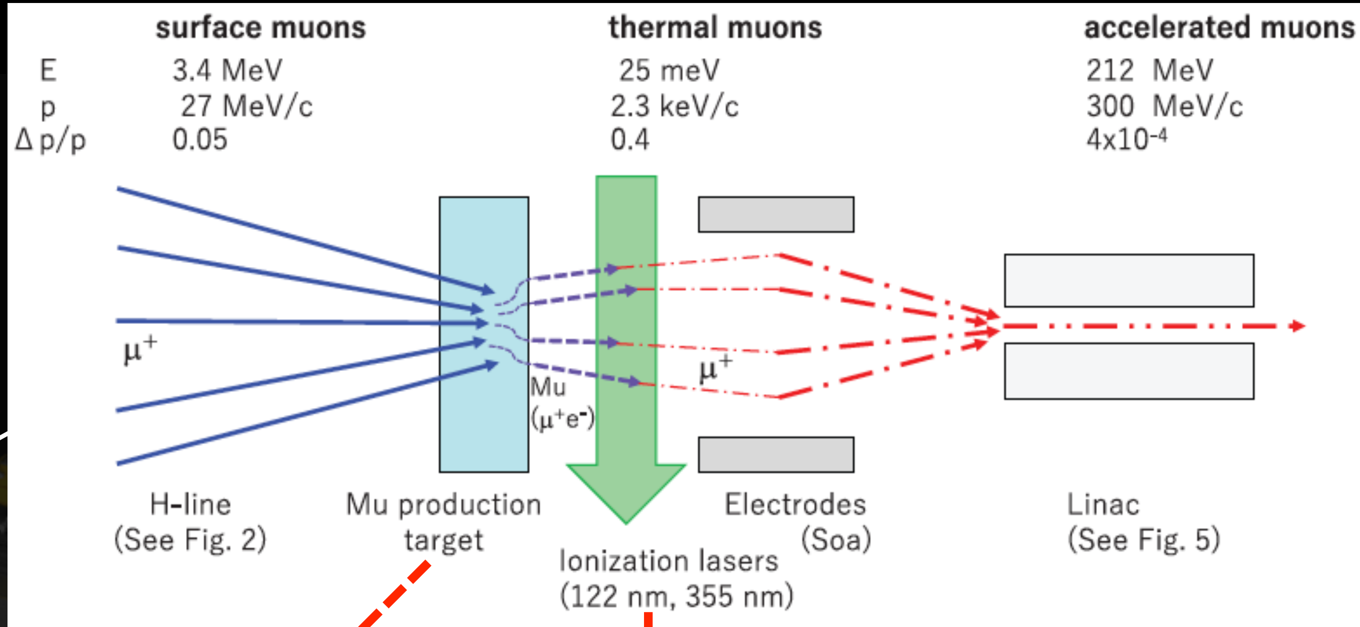
- The extension building is being ready for construction.





Thermal muons (1)



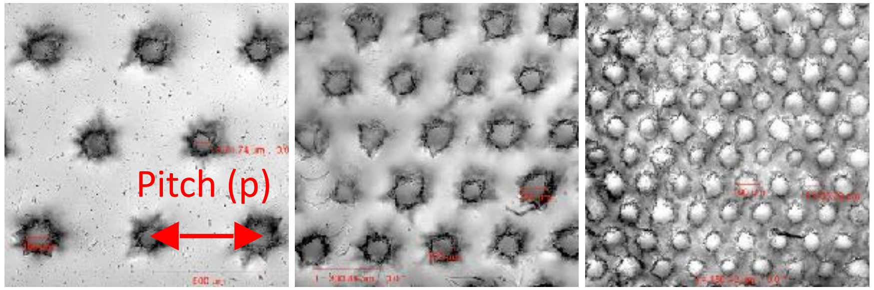


- Muonium (μ^+e^-, Mu) production
  - Cooling and diffusion in a form of Mu,
  - The polarization reduces to 50% due to the hyperfine states in the Mu formation,
  - Thermalization at room temperature,
  - Diffusion and emergence into vacuum following the Maxwell-Boltzmann distribution.

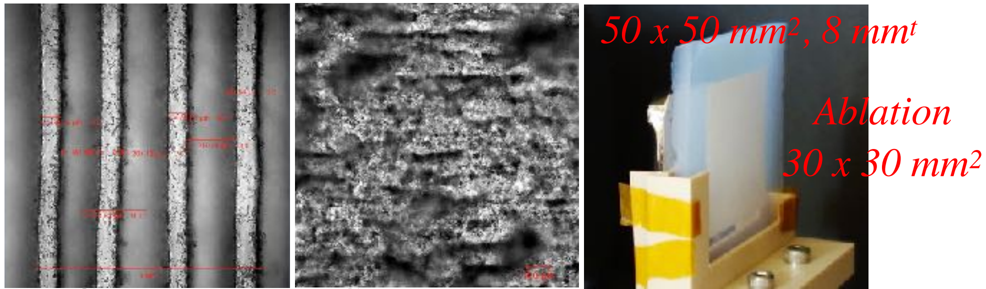
- Laser-resonant ionization
  - To produce thermal muons,
  - Using a high-power pulse laser.
  - 122 nm (Lyman-α) for μ-microscope.
  - 244 nm for Mu 1S-2S spectroscopy.

Thermal muons (2)

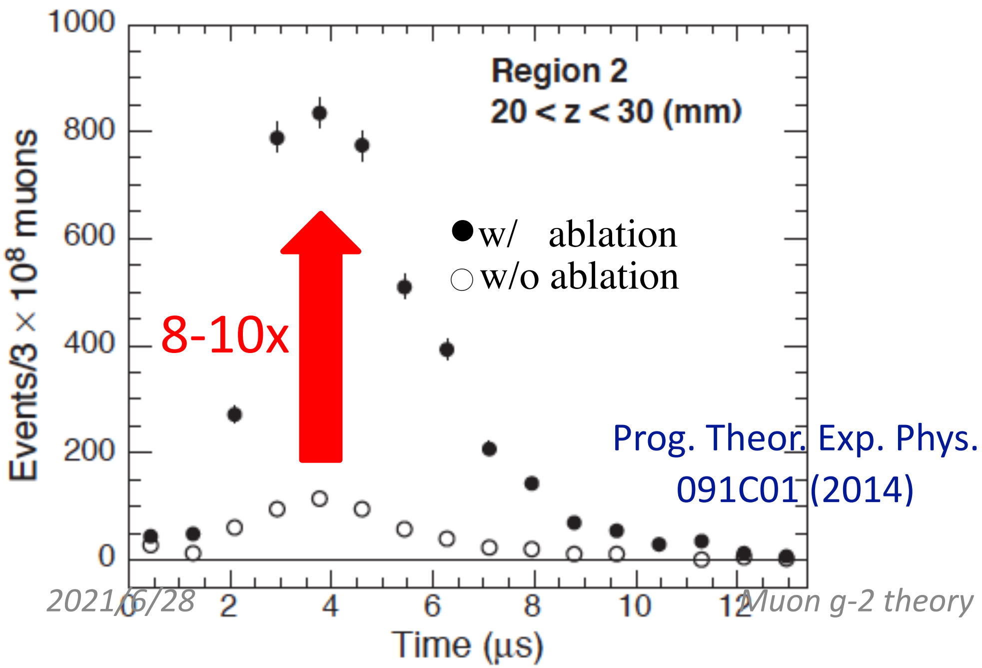
- Silica aerogel (SiO_2) for the muonium production target
  - Porous, similar to the silica powder.
  - Better handling in a beamline.
- Laser ablation on the surface improved the Mu emission rate.
  - The ablation structures could promote the diffusion.
  - Applicable to reach the BNL precision in ~2-year running.

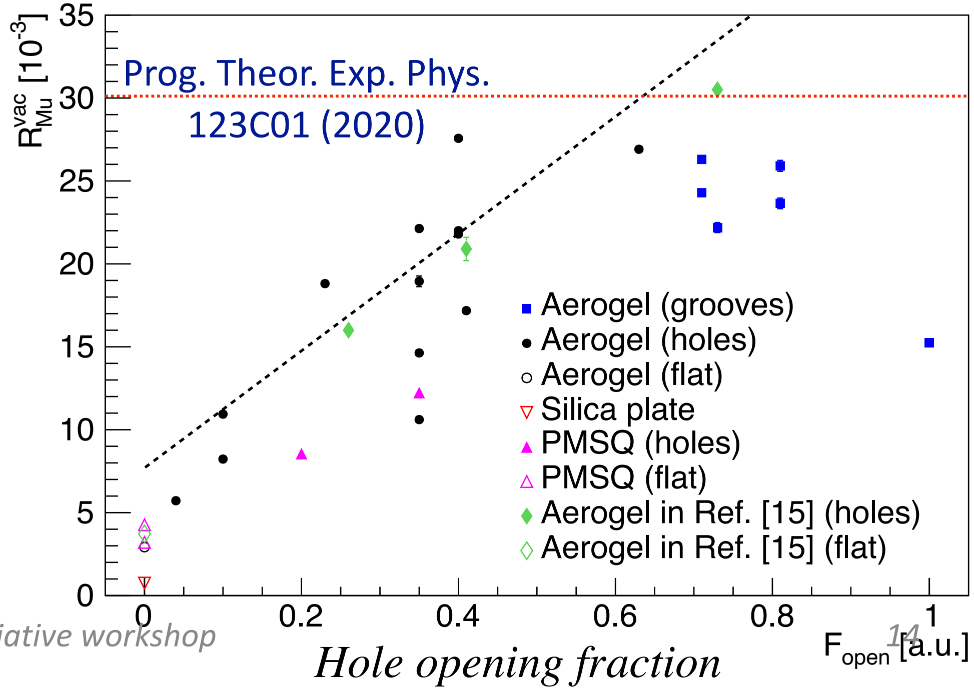


φ0.1 mm, p0.5, 0.3, 0.15 mm



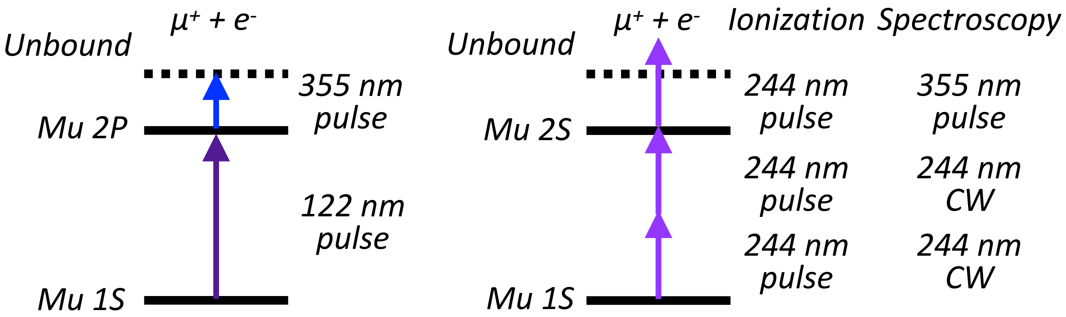
Grooves *Continuous* *Target size (typ.)*





Thermal muons (3)

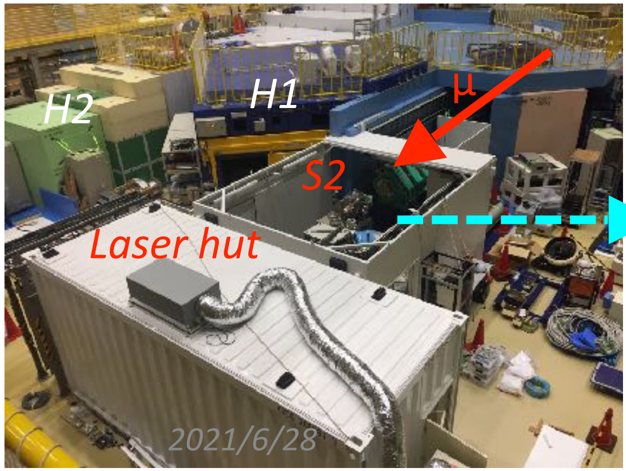
- Laser-resonant ionization needs to be examined.
  - A first priority in this and next years.



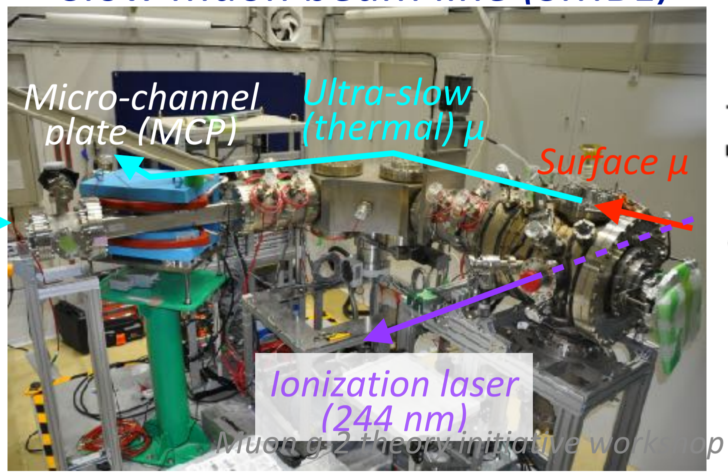
Project	Transmission μ-microscope (MLF U-line)	Mu 1S-2S spectroscopy (MLF S-line)
Wavelength	122 nm (VUV) →difficult handling	244 nm (DUV) →easier handling
Excitation process	One-photon exc. →higher prob.	Two-photon exc. →lower prob.
Technologies	Need challenging developments.	Established ones available.
Ionization rate (expected under a certain condition)	3% at 3 μJ.	1.6% at 200 mJ (x multi-pass amp.).

  - A dedicated beam will be available at MLF S-line from November 2021 for the Mu 1S-2S spectroscopy.

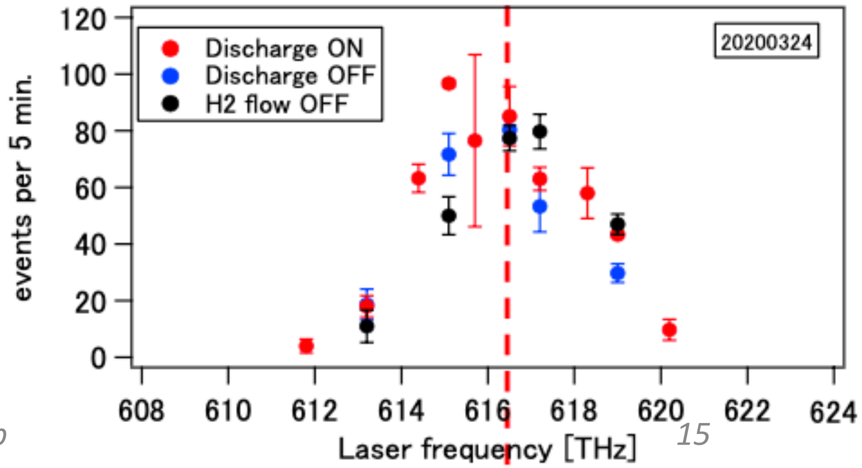
S2 area



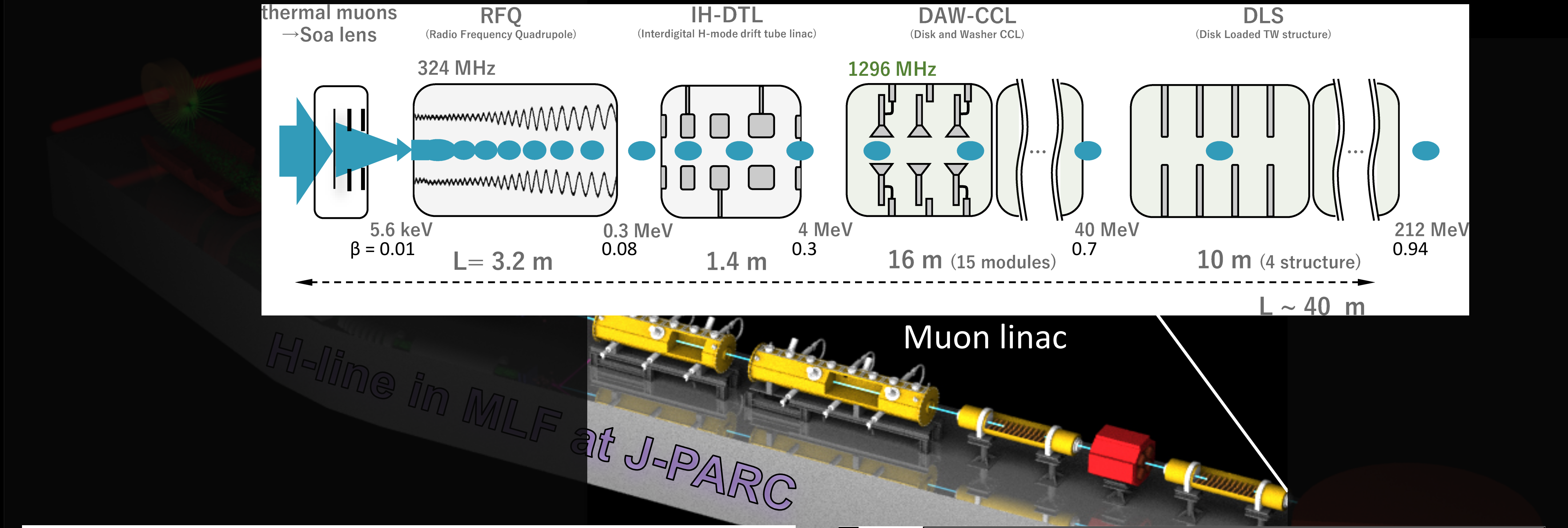
Slow muon beam line (SMBL)



Laser-resonant ionization of H atoms/compounds

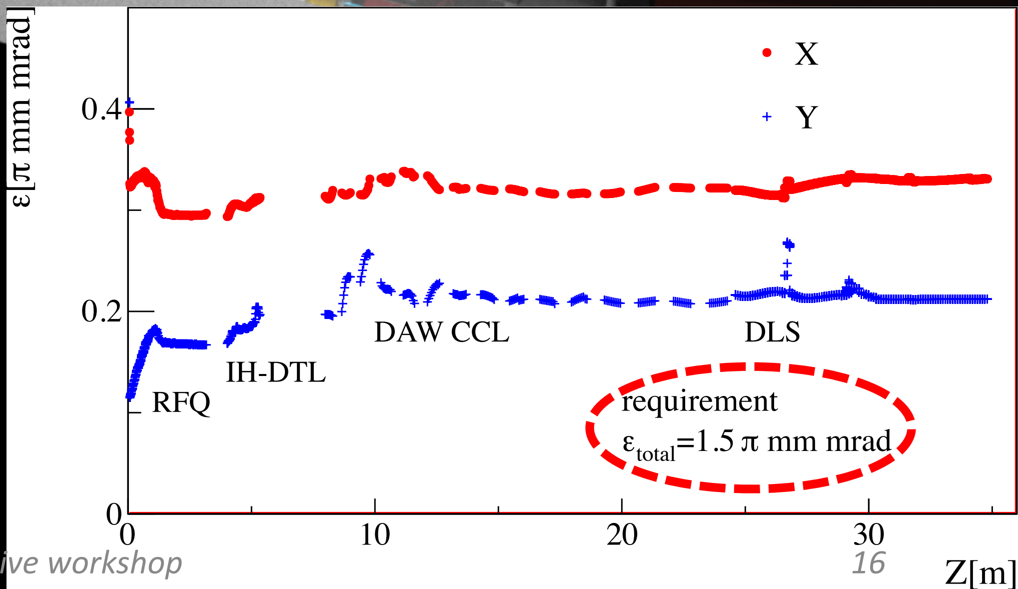


Muon linac (1)

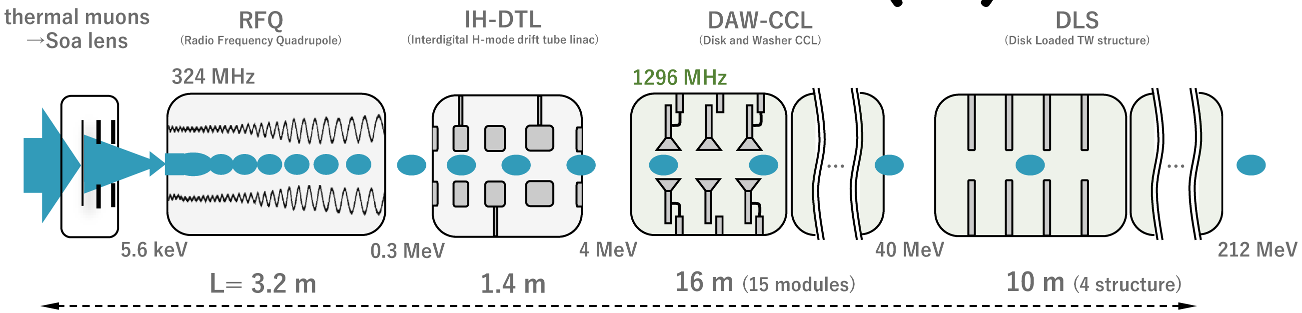


- Acceleration of the thermal muons suppressing the emittance growth.
  - From p-like acceleration to e-like one.

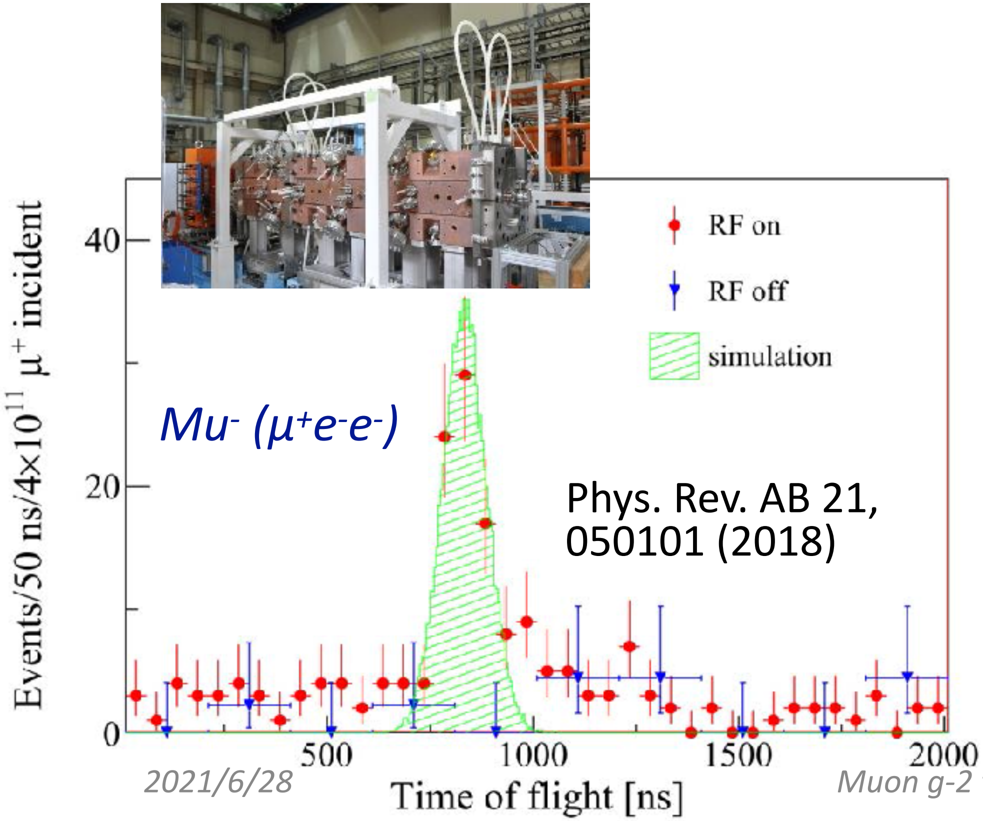
	Soa	RFQ	IH	DAW	DLS
Transmission (%)	87	95	100	100	100
Decay loss (%)	17	19	1	4	1
$\varepsilon_{n,\mathrm{rms},x}$ (π mm mrad)	0.38	0.30	0.32	0.32	0.33
$\varepsilon_{n,\mathrm{rms},y}$ (π mm mrad)	0.11	0.17	0.20	0.21	0.21



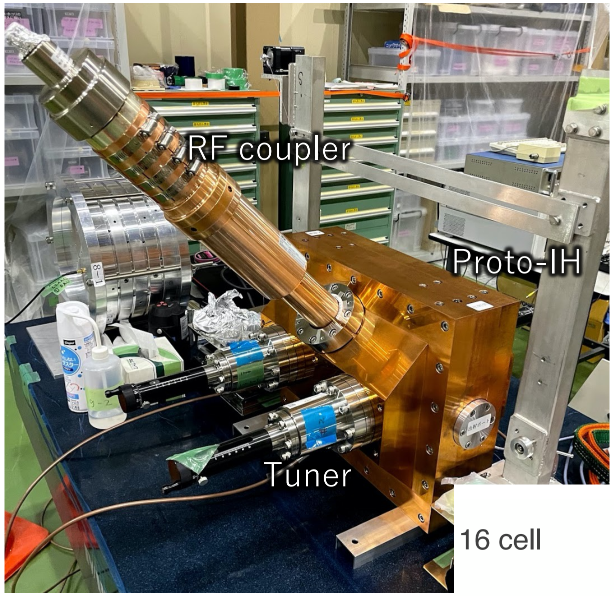
Muon linac (2)



- RFQ
  - World's first RF acceleration of μ (in Mu⁻).
  - RF acceleration of thermal μ is planned in FY2022.



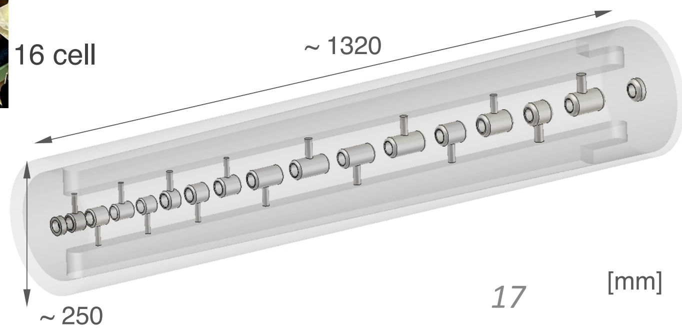
- IH-DTL
  - Prototype: under extensive tests.
  - Real IH-DTL: to be fabricated in FY2021.



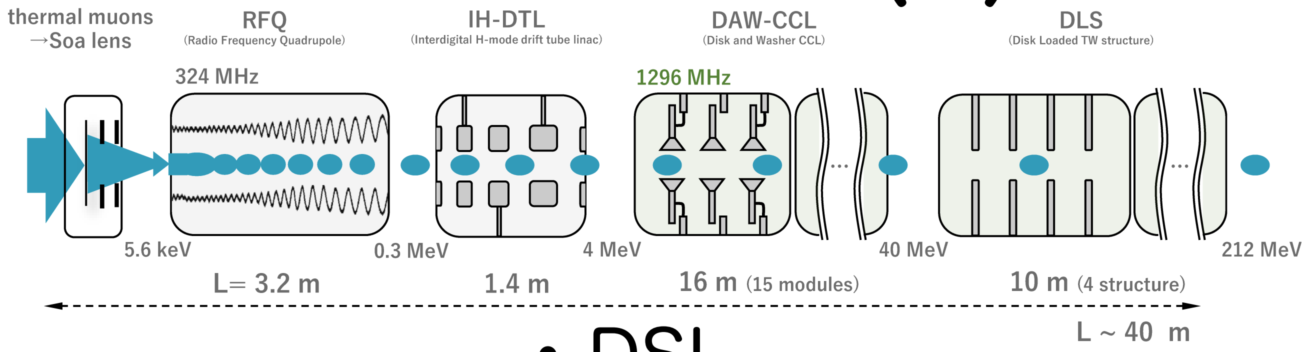
Proto IH-DTL (1/3 model)

Design: Phys. Rev. AB 19, 040101 (2016)

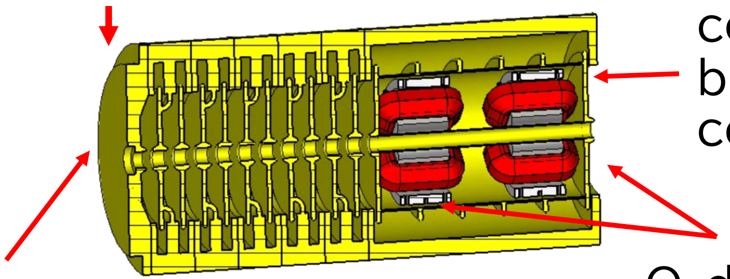
Real IH-DTL



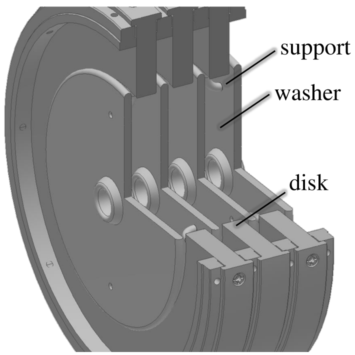
Muon linac (3)

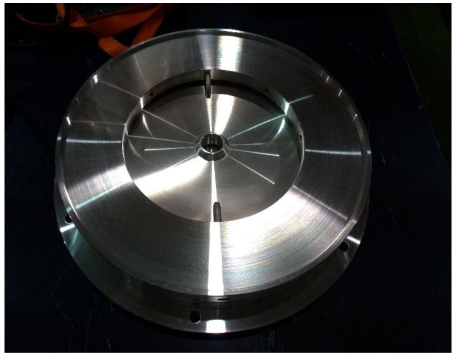


- DAW-CCL
  - The 1st tank: to be fabricated in FY2021.

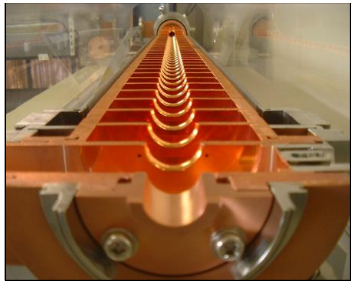


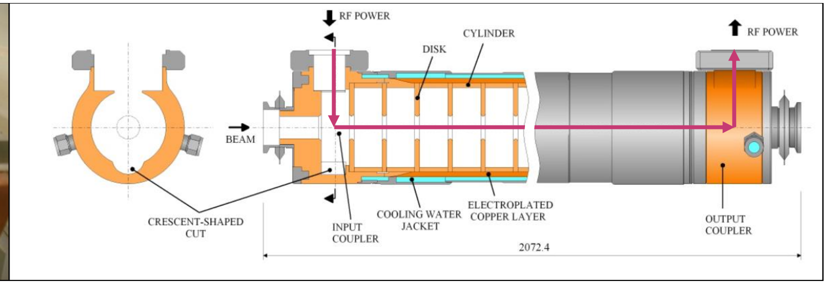
DAW tank (11 cells)





- DSL
  - Intended to nearly finalize the detailed design in FY2021.





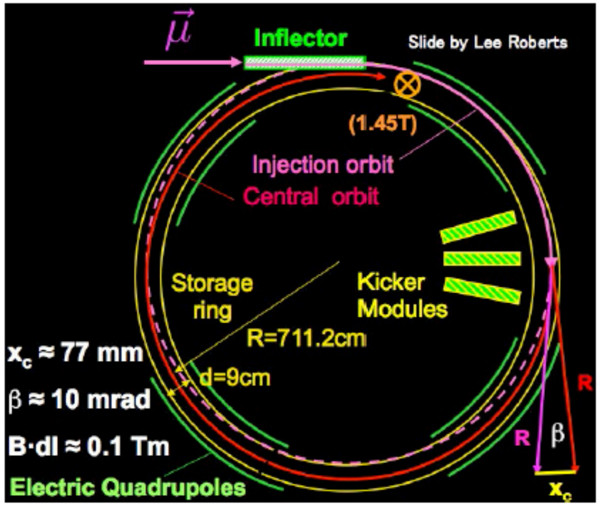
- Bunch width & beam profile monitors (BWM & BPM)
  - Various R&Ds are on-going.
    - *Micro-Channel-Plate (MCP)-based BWM,*
    - *CsI BPM (for the surface muons),*
    - *Silicon-on-Insulator (SOI) pixels for BPM,*
    - *Strip-line BPM.*

Injection (1)

- Need to develop the 3D spiral injection scheme for the small muon orbit.
  - 66 cm diameter orbit under the magnetic field of 3 T.
  - Extensive simulations to optimize the injection parameters and kicker spec., reflecting the magnet design updates.

3D spiral injection

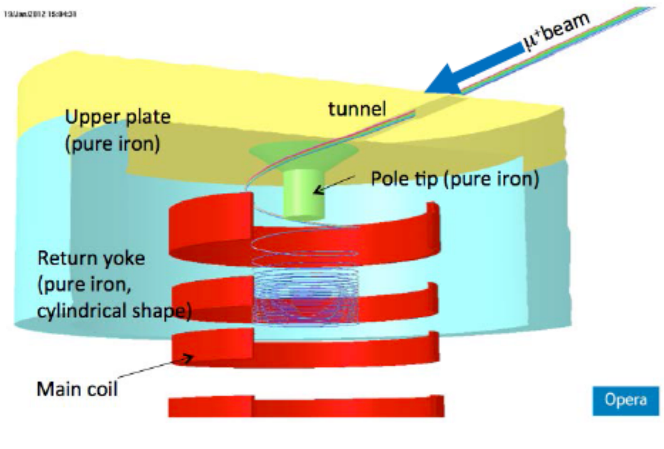
Horizontal injection + kicker (BNL E821, FNAL E989)



Injection efficiency : 3-5%(*)

(*) PRD73,072003 (2006)

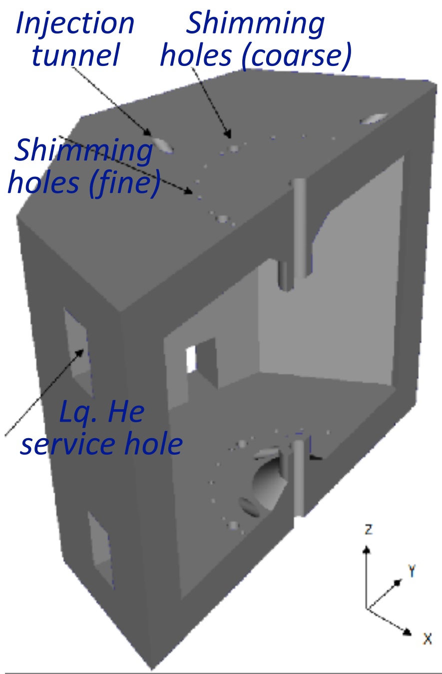
3D spiral injection + kicker (J-PARC E34)

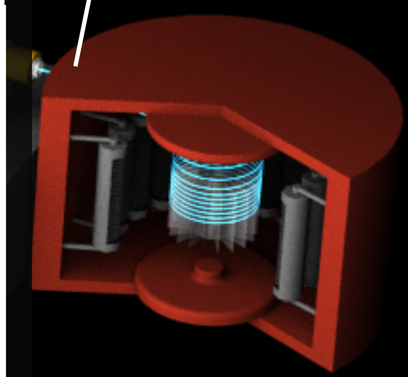


Injection efficiency : ~85%

H. Iinuma et al., Nucl. Instr. And Methods. A 832, 51 (2016)

Updated iron yoke

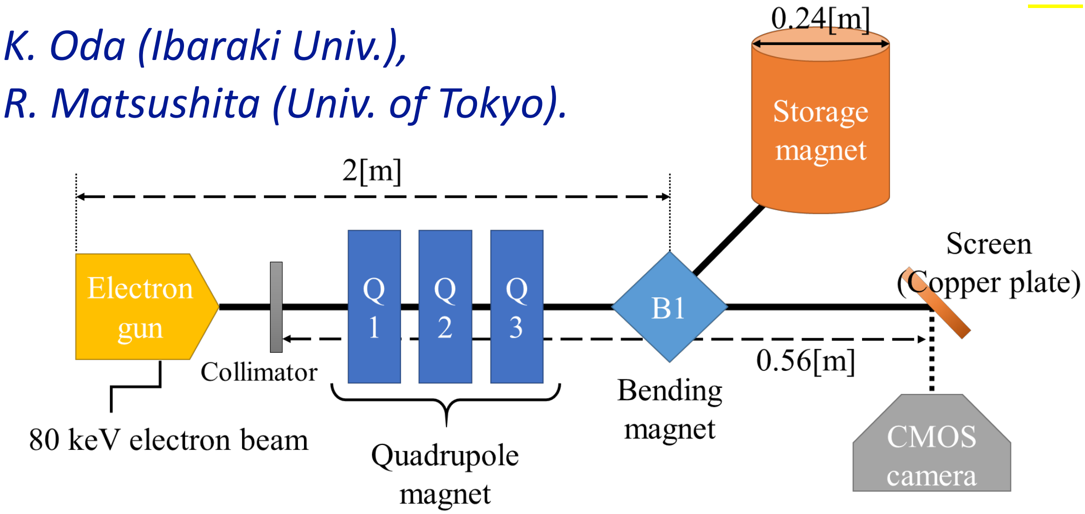




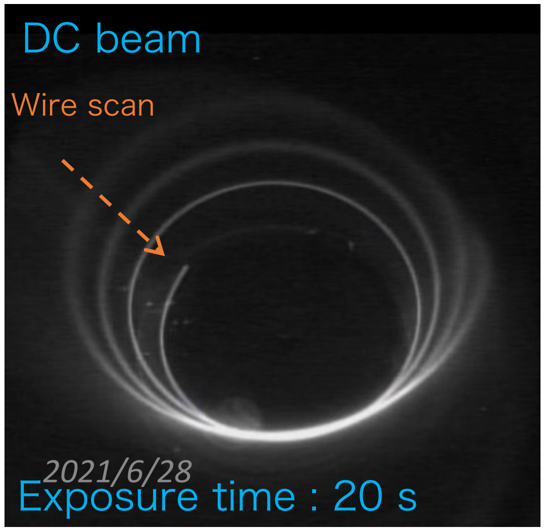
Injection (2)

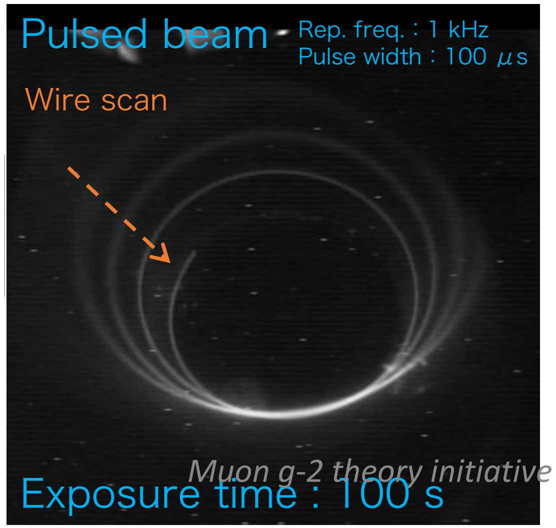
- In parallel, a demonstration experiment of the spiral injection using electrons is progressing well.
  - Started to use pulsed beams and to design the kicker.

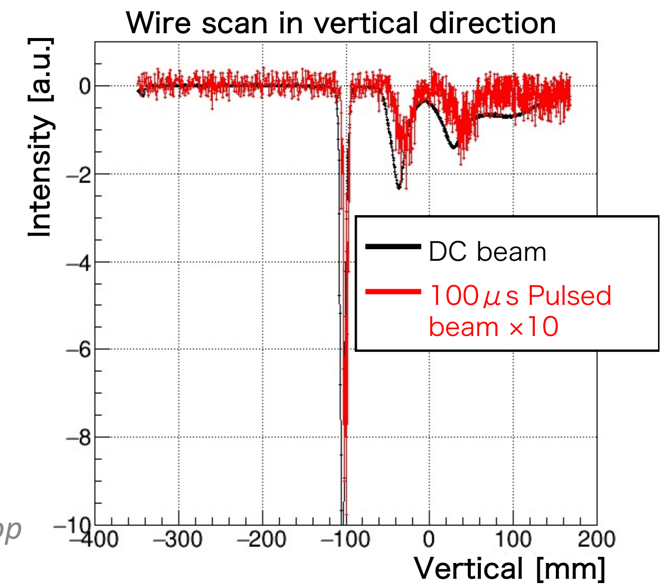
K. Oda (Ibaraki Univ.),
R. Matsushita (Univ. of Tokyo).



	J-PARC(E34)	Electron gun test bench
Diameter of the storage orbit	66 cm	24 cm
Storage field flux	3 T	82.5×10^{-4} T
Momentum	300 MeV/c	296.9 keV/c
Cyclotron period	7.4 ns	5.0 ns
Time to work the kicker magnetic field	130 ns	70 ns







Storage magnet (1)

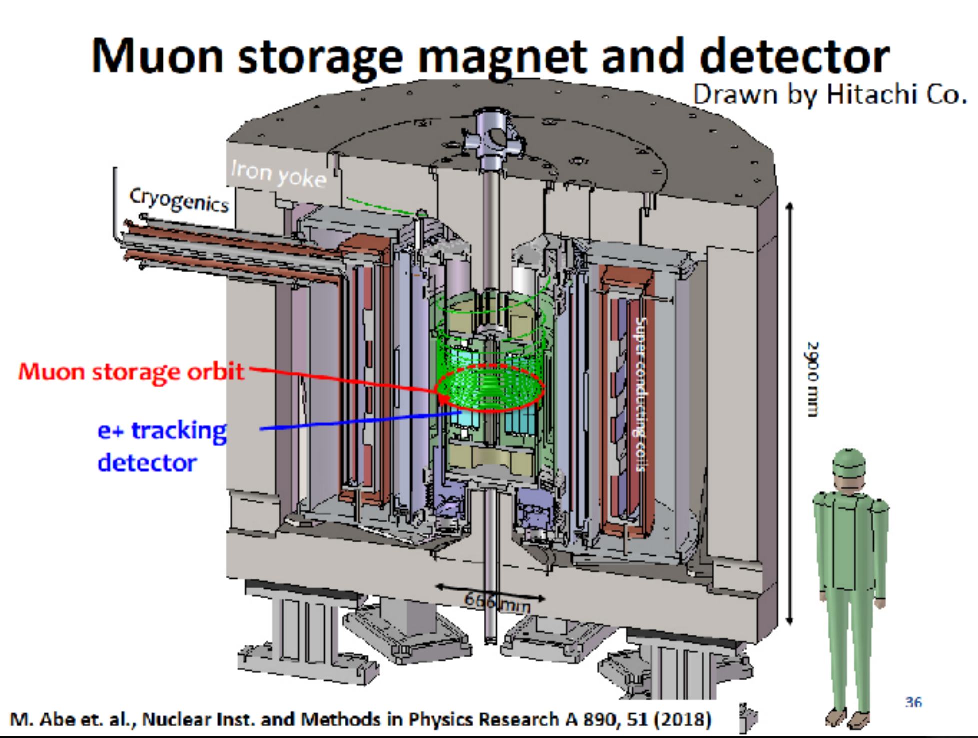
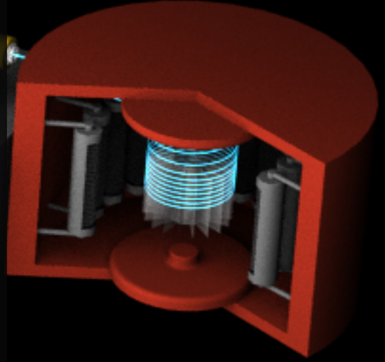


Table 3. Functions and specifications of the magnet system.

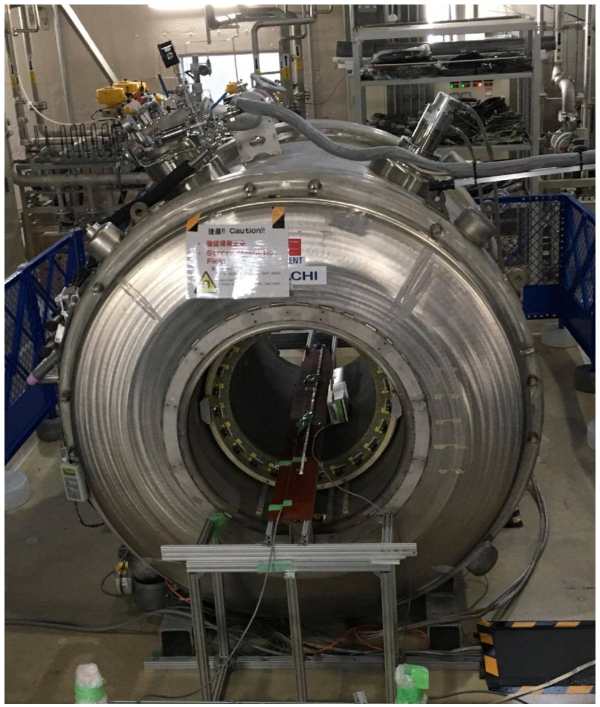
Functions	Location	Specifications
Main field	$r = 333 \pm 15$ mm, $z = \pm 50$ mm	Axial field (B_{0z}) = 3 T Local uniformity < 1000 ppb Integrated uniformity along the orbit less than 100 ppb (peak-to-peak)
Injection field	$0.4 < z < 1.1$ m	Radial field with $B_r \times B_z > 0$
Kicker field	$\|z\| < 0.4$ m	Radial pulsed field created by two pairs of round-type kicker coils.
Storage field	$r = 333 \pm 15$ mm, $z = \pm 50$ mm	Weak magnetic focusing, n-index $\sim (1.5 \pm 0.5) \times 10^{-4}$

MRI-type
storage magnet
(3 T, ϕ66-cm orbit)

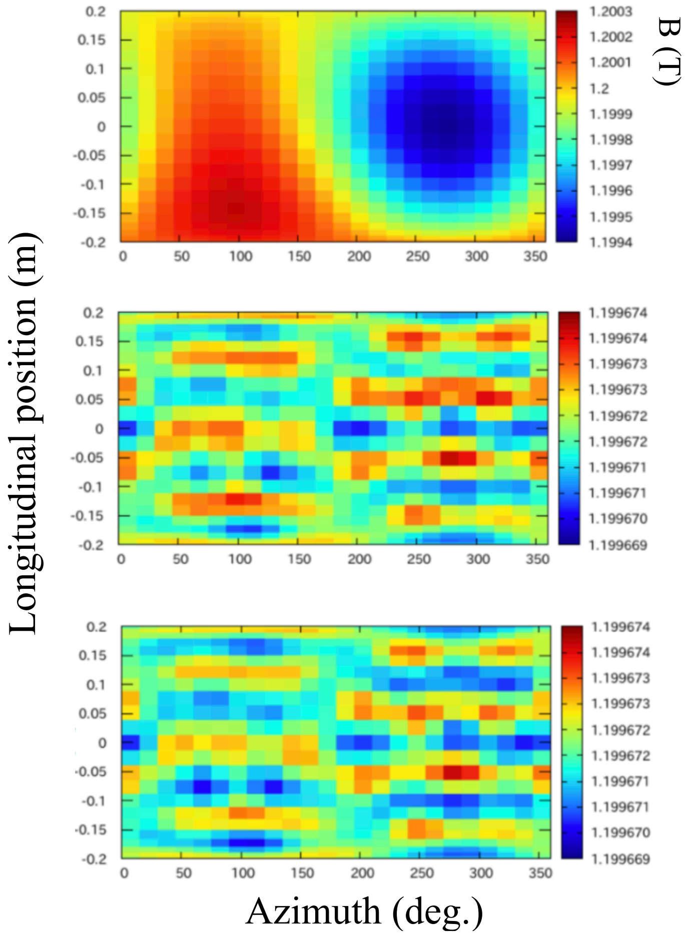


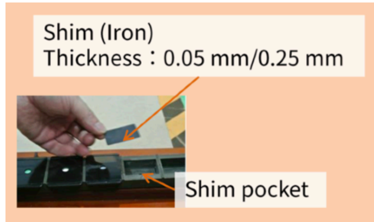
Storage magnet (2)

- Shimming studies for the fine control of magnetic field.
  - In collaboration with the Mu hyperfine spectroscopy (MuSEUM).
  - The procedure works well at 1.2 T (< 0.2 ppm, peak-to-peak).
  - Further tests will be carried out towards 3 T.

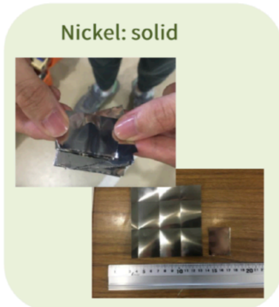


Superconducting magnet: 1.2 T
Axial length: 2 m,
Bore diameter: 925 mm.





Iron shim plates
341 ppm (p-p)



Nickel films
0.28 ppm (p-p)

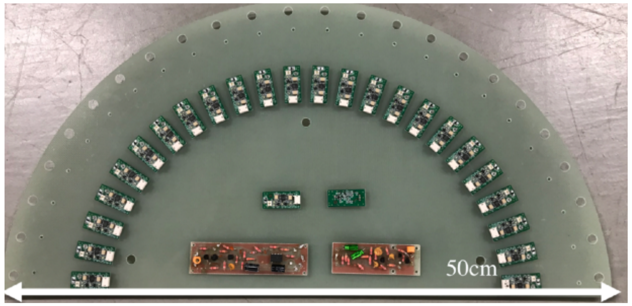
Magnetic putty
0.17 ppm (p-p)

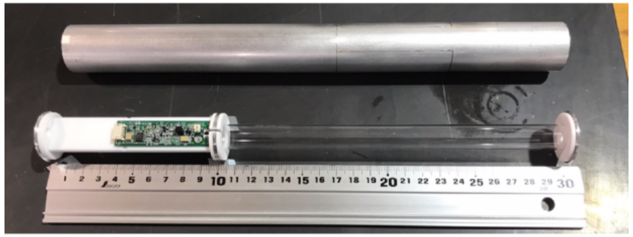
K. Sasaki, M. Abe (KEK),
M. Sugita, C. Oogane, H. Iinuma (Ibaraki U.)

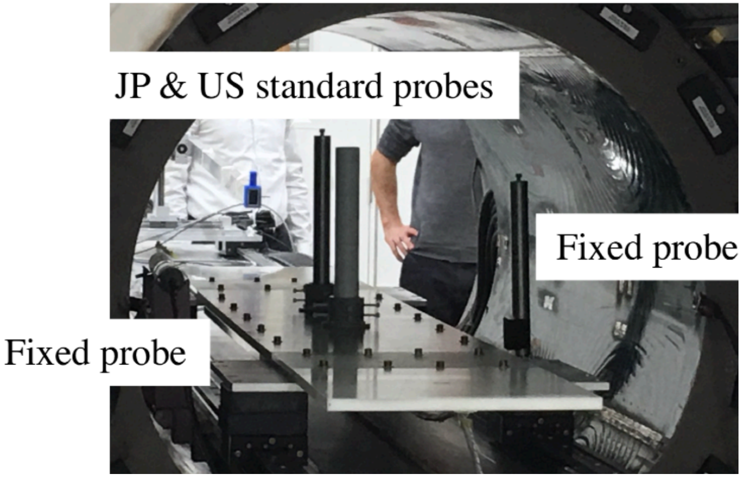
Slide from S. Kanda (KEK)

Storage magnet (3)

- Development of the field monitoring systems
  - In collaboration with the Mu hyperfine spectroscopy (MuSEUM).







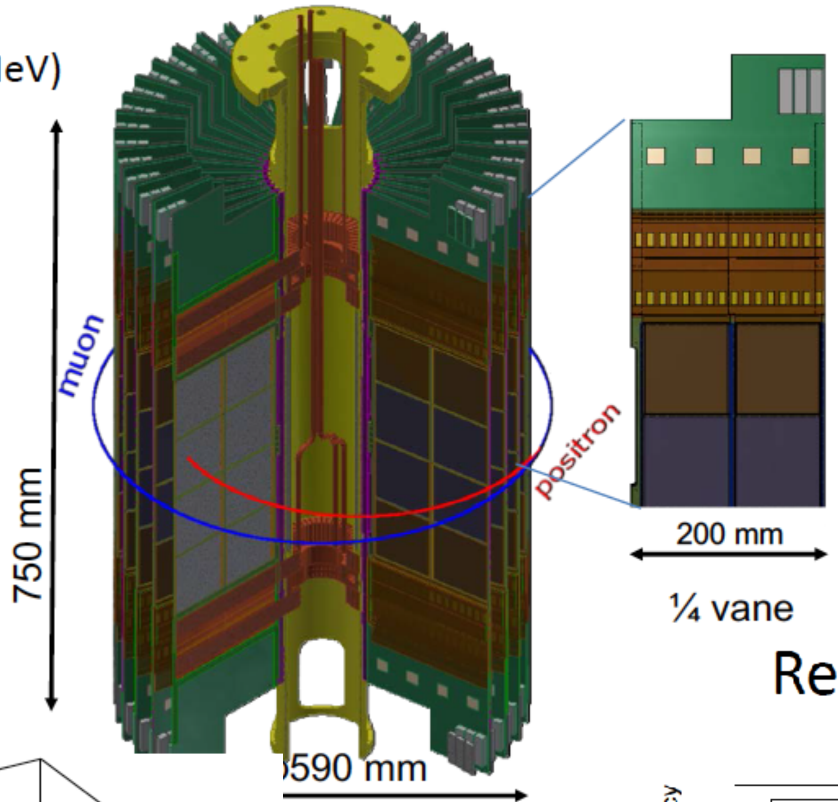
- Field camera
  - A 24-channel rotating NMR probe that maps magnetic fields in three dimensions.
  - Studies are underway for simultaneous multi-channel readouts.
  - K. Sasaki (KEK), A. Yamaguchi(KEK->JASRI),
    T. Tanaka, K. Shimizu (U. Tokyo), H. Tada (Nagoya U.)
- Fixed probe
  - A compact probe to monitor magnetic field stability during experiment.
- Standard probe
  - A high-precision NMR probe to calibrate others.
  - An accuracy of 15 ppb has been achieved.
  - Cross-calibration is underway in a joint research project between Japan and the US.
  - K. Sasaki (KEK), A. Yamaguchi(KEK->JASRI), T. Tanaka, S. Seo (U. Tokyo),
    P. Winter (ANL), D. Kawall (U. Mass.), D. Flay (U.Mass->JLab)

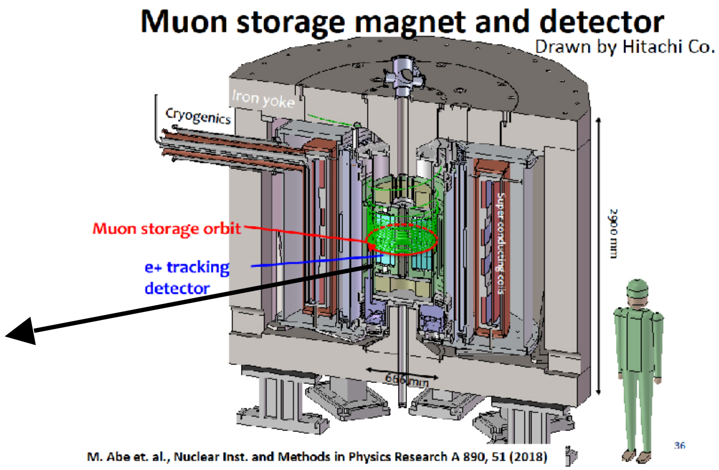
Slide from S. Kanda (KEK)

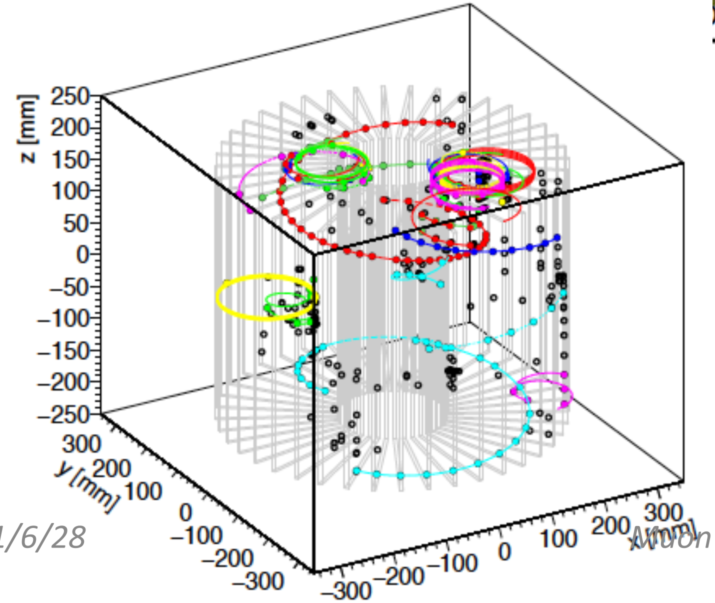
Positron tracking detector (1)

- Requirements
  - Detection of e+ (100<E<300 MeV)
  - Reconstruction of momentum vector
  - Stability over rate changes (1.4 MHz → 14 kHz)

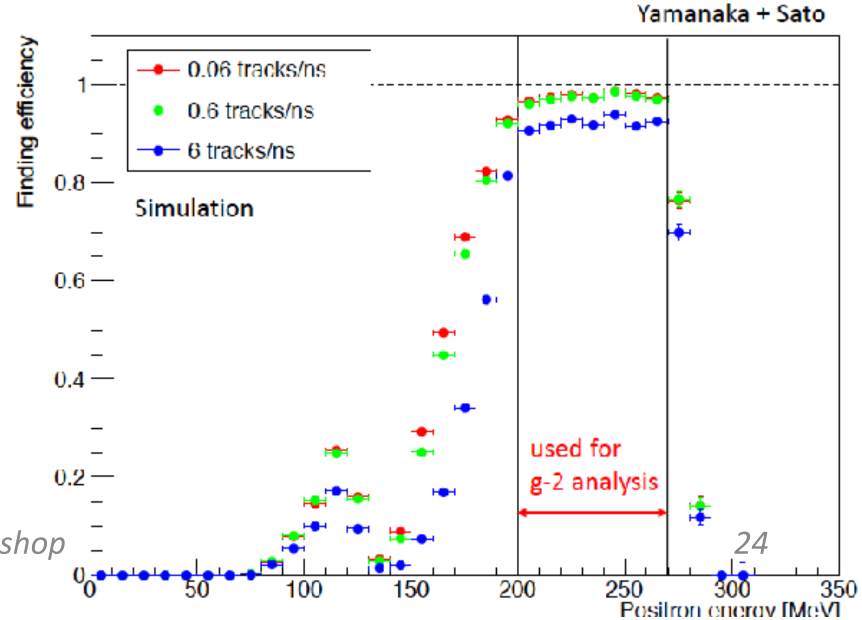
- Specifications
  - Sensor: p-on-n single-sided strip
  - Number of vanes: 40
  - Number of sensors : 640
  - Number of strips : 655,360
  - Area of sensors : 6.24 m^2







Reconstruction efficiency

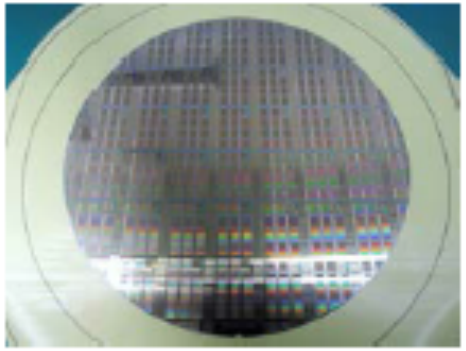


Positron tracking detector (2)

- Major components are in or completed the mass productions.
- Extensive studies and tests are on-going for the detector assembly.

Specification
2024 ch/piece
Line/space ~ 30/50 μm

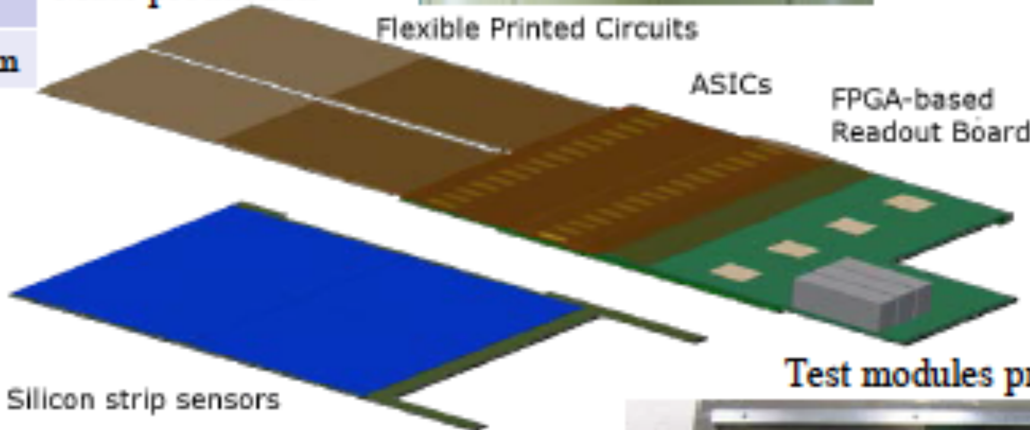
Design fixed
Mass production



Production version has been delivered. Evaluation is on-going.

Requirement
>4MIP range
1600e ENC@30 pF
128 ch/chip
5 nsec sampling

Quarter Vane



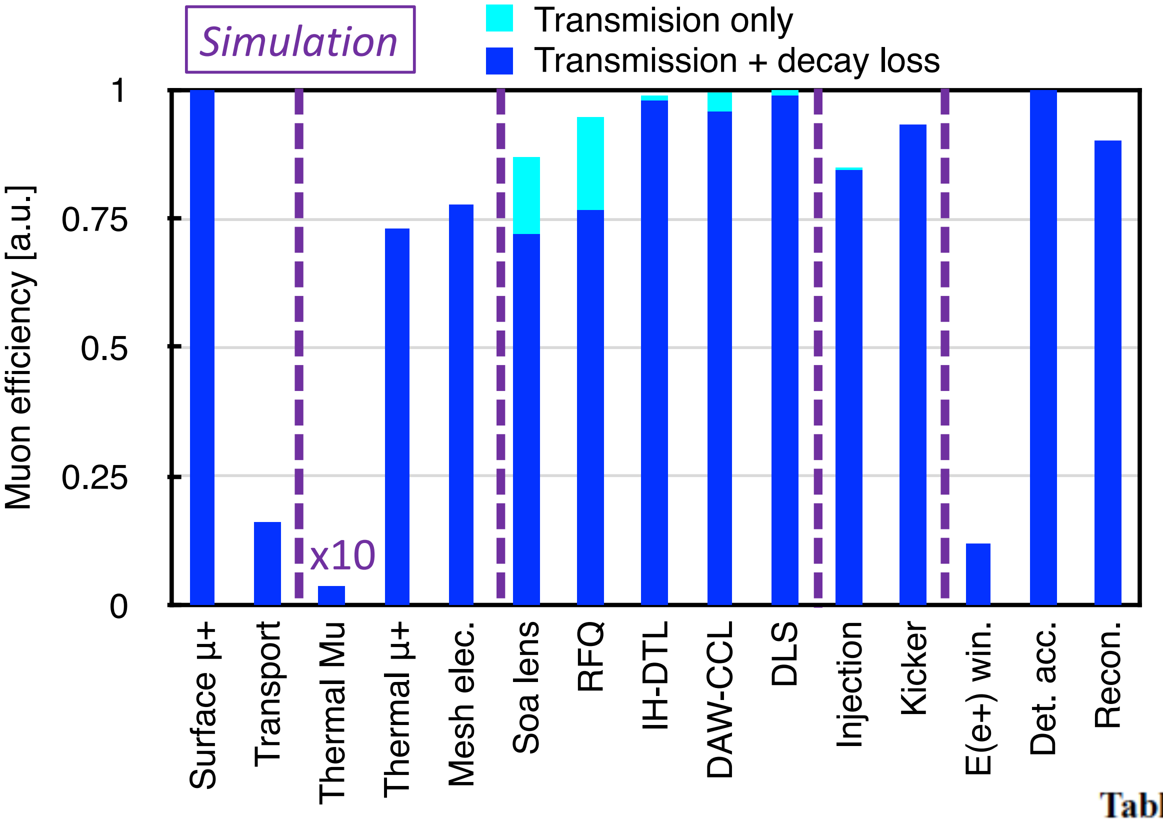
Design fixed.
Mass production.

Specification
98.77 mm × 98.77 mm
190 μm pitch
512 ch × 2 block

Test modules production/operation

->Mechanical moc. this JFY.

Expected sensitivities



- Overall μ^+ efficiency of $1.3\text{x}10^{-5}$.
- ~2-year running will reach the BNL precision of a_μ assuming
  - $2.2\text{x}10^7$ s data taking time,
  - 1 MW proton beam,
    - ➢ $5.7\text{x}10^{11}$ e^+'s for analysis,
  - 50% μ^+-polarization.

Expected uncertainties

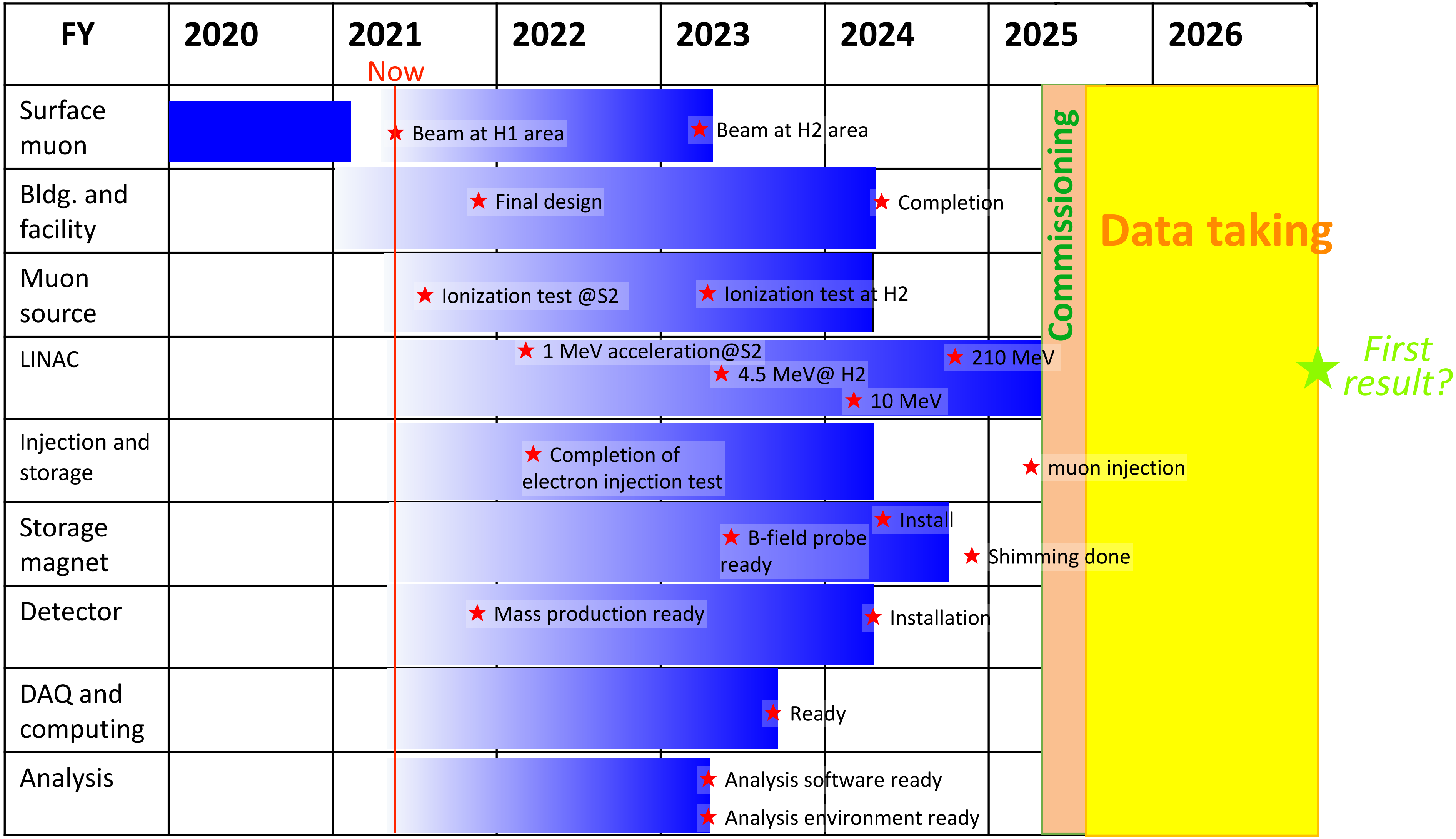
	Stat.	Syst.
δa_μ [ppb]	450	< 70
δEDM [10^{-21} e・cm]	1.5	0.36

Table 6. Estimated systmatic uncertainties on a_μ.

Anomalous spin precession (ω_a)		Magnetic field (ω_p)	
Source	Estimation (ppb)	Source	Estimation (ppb)
Timing shift	< 36	Absolute calibration	25
Pitch effect	13	Calibration of mapping probe	20
Electric field	10	Position of mapping probe	45
Delayed positrons	0.8	Field decay	< 10
Diffential decay	1.5	Eddy current from kicker	0.1
Quadratic sum	< 40	Quadratic sum	56

Systematic uncertainties will be much smaller than the statistical ones.

Intended schedule and milestones



- The experiment was endorsed as the near-term priority by KEK Science Advisory Committee (SAC) (2019.3).
- KEK prepares for the funding request to MEXT (2020.6-).

Collaboration

- Now 116 members from Canada , China, Czech, France, Japan, Korea, Russia and USA, and still growing.
- New collaborators are highly welcome.

Summary

- J-PARC E34 intends to measure the muon g-2 and EDM with a new experimental approach.
  - Very different experimental approach from that of the BNL/FNAL experiments.
    - ✓ Small-emittance muon beam with no strong focusing,
    - ✓ MRI-type storage ring with a good injection efficiency and high uniformity of local B-field,
    - ✓ Full-tracking detector with large acceptance.
- The experiment is getting ready for realization.
  - The development and construction is in progress to start data taking in FY2025.
    - ✓ R&Ds of the experimental apparatus keep progressing well,
    - ✓ Funding requests are being made to MEXT,
    - ✓ Intending to reach the BNL precision in ~2-year running.